ARCHIE, G.E., 1942

THE ELECTRICAL RESISTIVITY LOG AS AN AID IN DETERMINING SOME RESERVOIR CHARACTERISTICS

The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics

BY G. E. ARCHIE*

(Dallas Meeting, October 1941)

THE usefulness of the electrical resistivity log in determining reservoir characteristics is governed largely by: (1) the accuracy with which the true resistivity of the formation can be determined; (2) the scope of detailed data concerning the relation of resistivity measurements to formation characteristics; (3) the available information concerning the conductivity of connate or formation waters; (4) the extent of geologic knowledge regarding probable changes in facies within given horizons, both vertically and laterally, particularly in relation to the resultant effect on the electrical properties of the reservoir. Simple examples are given in the following pages to illustrate the use of resistivity logs in the solution of some problems dealing with oil and gas reservoirs. From the available information, it is apparent that much care must be exercised in applying to more complicated cases the methods suggested. It should be remembered that the equations given are not precise and represent only approximate relationships. It is believed, however, that under favorable conditions their application falls within useful limits of accuracy.

INTRODUCTION

The electrical log has been used extensively in a qualitative way to correlate formations penetrated by the drill in the exploitation of oil and gas reservoirs and to provide some indication of reservoir content. However, its use in a quantitative way has been limited because of various factors that tend to obscure the significance of the electrical readings obtained. Some of these factors are the borehole size, the resistivity of the mud in the borehole, the effect of invasion of the mud filtrate into the formation, the relation of the recorded thickness of beds to electrode spacing, the heterogeneity of geologic formations, the salinity or conductivity of connate water, and, perhaps of greatest importance, the lack of data indicating the relationship of the resistivity of a formation *in situ* to its character and fluid content.

On the Gulf Coast it is found that the effects of the size of the borehole and the mud resistivity are generally of little importance, except when dealing with high formational resistivities or extremely low mud resistivities. Fortunately, little practical significance need be attached to the exact values of the higher resistivities recorded. Low mud resistivities are not common, but when this condition is encountered it may be corrected by replacing the mud column. With the present advanced knowledge of mud control, invasion of mud filtrate into sands can be minimized, thereby increasing the dependability of the electrical log. The effect of electrode spacing on the recorded thickness of a bed is often subject to compensation or can be sufficiently accounted for to provide an acceptable approximation of the true resistivity of the formation. As development of a field or area progressively enhances the knowledge of the lithologic section, the resistivity values of the electrical log take on greater significance, ultimately affording acceptable interpretations. The salinity, and

Manuscript received at the office of the Institute Sept. 27; revised Dec. 8, 1941. Issued as T.P. 1422 in PETROLEUM TECHNOLOGY, January 1942.
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therefore the conductivity, of the connate water associated with the various producing horizons may be determined with sufficient accuracy by the usual sampling procedure.

Determination of the significance of the resistivity of a producing formation as recorded by the electrical log appears, for the present at least, to rest largely with the application of empirical relationships established in the laboratory between certain of the physical properties of a reservoir rock and what may be termed a formation factor. It should be stressed at this point that numerous detailed laboratory studies of the physical properties of the formations in relation to the electrical measurements in question are essential to a reliable solution of the problems dealing with reservoir content. The purpose of this paper is to present some of these laboratory data and to suggest their application to quantitative studies of the electrical log. It is not intended to attempt to discuss individual resistivity curves and their application. The disturbing factors (borehole, bed thickness, and invasion) are discussed briefly only to indicate instances when they are not likely to affect the usefulness of the observed resistivity.

Resistivity of Sands when Pores Are Entirely Filled with Brine

A study of the resistivity of formations when all the pores are filled with water is of basic importance in the detection of oil or gas by the use of an electrical log. Unless this value is known, the added resistivity due to oil or gas in a formation cannot be determined.

The resistivities of a large number of brine-saturated cores from various sand formations were determined in the laboratory; the porosity of the samples ranged from 10 to 40 per cent. The salinity of the electrolyte filling the pores ranged from 20,000 to 100,000 milligrams of NaCl per liter. The following simple relation was found to exist for that range of porosities and salinities:

$$R_o = FR_w \qquad [1]$$

where R_o = resistivity of the sand when all the pores were filled with brine, R_w = resistivity of the brine, and F = a "formation resistivity factor."

In Figs. 1 and 2, F is plotted against the permeabilities and porosities, respectively, of the samples investigated. The data presented in Fig. 1 were obtained from consolidated sandstone cores in which the cementing medium consisted of various amounts of calcareous as well as siliceous materials. The cores had essentially the same permeability, parallel to and perpendicular to the bedding of the layers. All of the cores were from producing zones in the Gulf Coast region. Cores from the following fields were used: Southeast Premont, Tom Graham, Big Dome-Hardin, Magnet-Withers, and Sheridan, Texas; also La Pice, and Happytown, La. Fig. 2 presents similar data obtained from cores of a widely different sandstone; that is, one that had extremely low permeability values compared with those shown in Fig. 1 for corresponding porosities. These cores were from the Nacatoch sand in the Bellevue area, Louisiana.

From Figs. 1 and 2 it appears that the formation resistivity factor F is a function of the type and character of the formation, and varies, among other properties, with the porosity and permeability of the reservoir rock; many points depart from the average line shown, which represents a reasonable relationship. Therefore, individual determinations from any particular core sample may deviate considerably from the average. This is particularly true for the indicated relationship to permeability. Further, although the variation of F with porosity for the two groups of data taken from sands of widely different character is quite consistent, the effect

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of variations in permeability on this factor is not so evident. Naturally the two relationships could not be held to apply with equal rigor because of the well

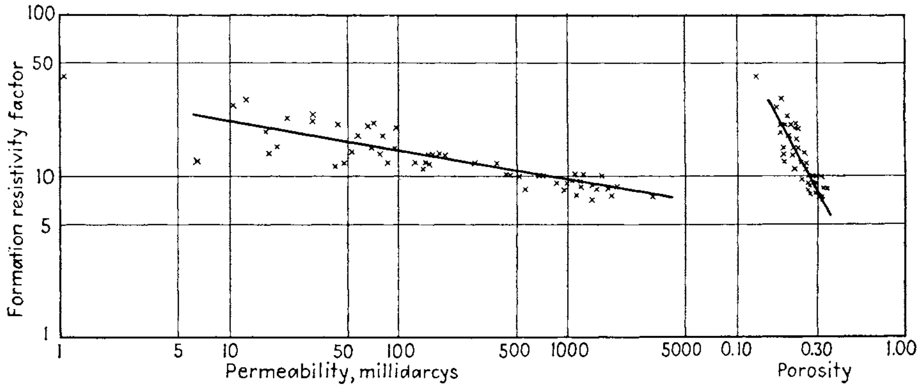

FIG. 1.—RELATION OF POROSITY AND PERMEABILITY TO FORMATION RESISTIVITY FACTOR FOR CONSOLIDATED SANDSTONE CORES OF THE GULF COAST.

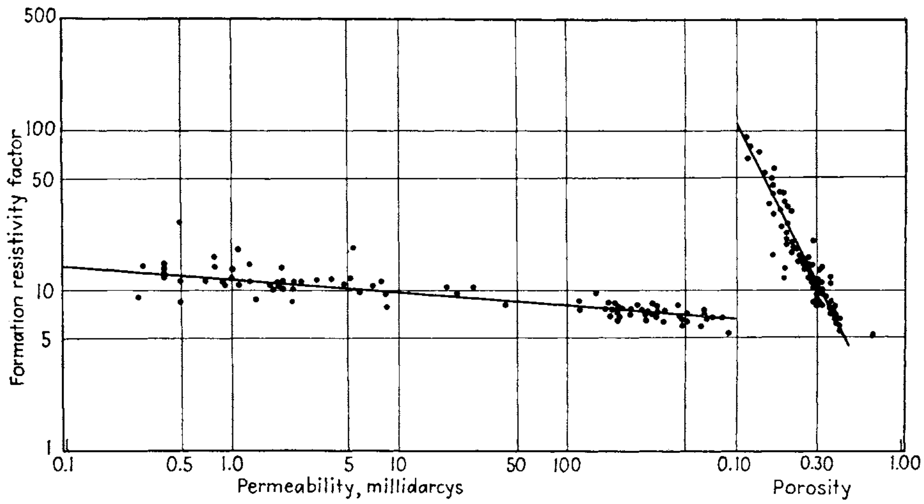

FIG. 2.—RELATION OF POROSITY AND PERMEABILITY TO FORMATION RESISTIVITY FACTOR, NACATOCH SAND, BELLEVUE, LA.
Permeabilities below 0.1 millidarcy not recorded.

established fact that permeability does not bear the same relation to porosity in all sands. From close inspection of these data, and at the present stage of the investigation, it would appear reasonably accurate to accept the indicated relationship between the formation resistivity factor and porosity. Thus, knowing the porosity of the sand in question, a fair estimate may be made of the proper value to be assigned to F, based upon the indicated empirical relationship

$$F = \theta^{-m} \qquad [2]$$

or from Eq. 1,

$$R_o = R_w\theta^{-m} \qquad [3]$$

where θ is the porosity fraction of the sand and m is the slope of the line representing the relationship under discussion.

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From a study of many groups of data, m has been found to range between 1.8 and 2.0 for consolidated sandstones. For clean unconsolidated sands packed in the laboratory, the value of m appears to be about 1.3. It may be expected, then, that the loosely or partly consolidated sands of the Gulf Coast might have a value of m anywhere between 1.3 and 2.

Resistivity of Formations when Pores Are Partly Filled with Brine, the Remaining Voids Being Filled with Oil or Gas

Various investigators—Martin,[1] Jakosky,[2] Wyckoff,[3] and Leverett[4]—have studied the variation in the resistivity of sands due to the percentage of water contained in the pores. This was done by displacing varying amounts of conducting water from the water-saturated sand with nonconducting fluid. Fig. 3 shows the relation which the various investigators found to exist between S (fraction of the voids filled with water) and R (the resulting resistivity of the sand) plotted on logarithmic coordinates. For water saturations down to about 0.15 or 0.20, the following approximate equation applies:

$$S = \left(\frac{R_o}{R}\right)^{\frac{1}{n}} \quad \text{or} \quad R = R_o S^{-n} \qquad [4]$$

For clean unconsolidated sand and for consolidated sands, the value of n appears to be close to 2, so an approximate relation can be written:

$$S = \sqrt{\frac{R_o}{R}} \qquad [5]$$

or from Eq. 1,

$$S = \sqrt{\frac{FR_w}{R}} \qquad [6]$$

Since in the laboratory extremely short intervals of time were allowed for the establishment of the equilibrium conditions compared with underground reservoirs, there is a possibility that the manner in which the oil or gas is distributed in the pores may be so different that these relations derived in the laboratory might not apply underground.

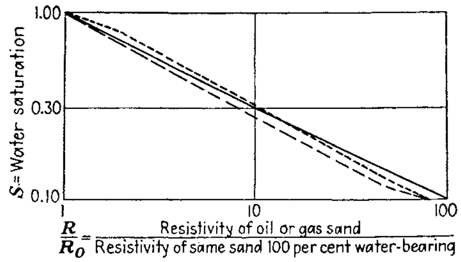

FIG. 3.—RELATION OF S TO $\frac{R}{R_o}$

Legend and Data

Curve	Investigator	Type Sand	Salinity of Water, Grams NaCl per Liter	Oil or Gas	Porosity Fraction
——	Wyckoff	Various		CO_2	Various
——	Leverett	Uncons.	8 approx.	Oil	0.40
– – –	Martin	Cores	130	Oil	0.20 and 0.45(?)
------	Jakosky	Friable	29 approx.	Oil	0.23

Considerable encouragement on this point is established, however. For example, Eq. 4 appears to hold even though gas or oil is the nonconducting phase. Each probably assumes a different distribution in the pores, yet the resulting resistivity is not appreciably changed. Also, no great change is found in the average relation between the formation resistivity factor and porosity for changes in types of consolidated sandstones. This indicates that even though the oil or gas underground may fill the pore space in a different manner from that in the short-time laboratory experiments, the relationship expressed by Eq. 4 should apply equally well underground.

Basic Resistivity Values to Be Obtained in Estimating Fluid Content of a Sand

The foregoing discussion indicates that the basic values to be obtained are: (1) the resistivity of the sand in question under-

[1] References are at the end of the paper.

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ground (R), and (2) the resistivity of the same sand when its pores are entirely filled with connate water (R_o).

The first value can be obtained from the electrical log when all factors can be properly weighed. The latter may also be obtained from the log when a log is available on the same horizon where it is entirely water-bearing. Of course, this is true only when the sand conditions, particularly porosity, are the same as at the point in question and when the salinity of the connate or formation water throughout the horizon is the same.

In a water-drive reservoir, or any reservoir where the connate water is in direct contact with the bottom or edge water, there should be no appreciable difference in the salinities through the horizon, at least within the limits set forth for the operation of Eqs. 1 and 4; that is, when the salinity of the connate water is over 20,000 mg. NaCl per liter and the connate water is over 0.15. In depletion-type reservoirs, or when connate water is not in direct contact with bottom or edge water, special means may have to be devised to ascertain the salinity of the connate water.

When it is not possible to obtain R_o in the manner described above, the value can be approximated from Eq. 3, θ and m having been determined by core analyses and R_w by regular analyses.

Calculation of Connate Water, Porosity and Salinity of Formation Water from the Electrical Log

The resistivity scale used by the electrical logging companies is calculated assuming the electrodes to be points in a homogeneous bed.[5] Therefore, the values recorded must be corrected for the presence of the borehole, thickness of the layers in relation to the electrode spacing, and any other condition different from the ideal assumptions used in calculating the scale.

Consider a borehole penetrating a large homogeneous layer, in which case the electrode spacing is small in comparison with the thickness of the layer. If the resistivity of the mud in the hole is the same as the resistivity of the layer, there will be, of course, no correction for the effect of the borehole. If the resistivity of the mud differs from the resistivity of the layer, there will be a correction. Table 1 shows approximately how the presence of the borehole changes the observed resistivity for various conditions. The third curve, or long normal, of the Gulf Coast is considered because this arrangement of electrodes gives very nearly a symmetrical picture on passing a resistive layer and has sufficient penetration in most instances to be little affected by invasion when the filtrate properties of the mud are suitable.

Table 1.—*Effect of Borehole on Infinitely Large Homogeneous Formation*

True Resistivity of Formation, Meter-ohms	Observed Resistivity on Electric Log			
	In an 8-in. Borehole		In a 15-in. Borehole	
	Resistivity of Mud in Hole (at Bottom-hole Temperature) of		Resistivity of Mud in Hole (at Bottom-hole Temperature) of	
	0.5 Meter-ohms	1.5 Meter-ohms	0.5 Meter-ohms	1.5 Meter-ohms
0.5	0.5	0.5	0.5	0.5
1	1	1	1	1
5	6	5	5	5
10	12	11	11	11
50	65	65	50	55

The values in Table 1 have been calculated assuming a point potential "pick-up" electrode 3 ft. away from a point source of current, other electrodes assumed to be at infinity, and it has been found that the table checks reasonably well with field observations. Checks were made by: (1) measuring the resistivity of shale and other cores whose fluid content does not change during the coring operation and extraction from the well; (2) measuring the resistivity of porous cores from water-bearing formations after these cores were

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resaturated with the original formation water. Adjustment due to temperature difference, of course, is necessary before the laboratory measurement is compared with the field measurement.

TABLE 2.—*Effect of Formation Thickness, No Borehole Present*

True Resistivity	Observed Resistivity		
Layer between Large Shale Bodies Having Resistivity of 1.0 Meter-ohms	Thickness of Layer		
	24 Ft.	16 Ft.	8 Ft.
1	1	1	1
5	5	5	3
10	10	9	6
20	20	19	11

The correction at the higher resistivities appears to be appreciable. However, in the Gulf Coast when the value of R_o is low the correction is not so important. For example, assume a friable oil sand whose true resistivity is 50 meter-ohms and whose resistivity when entirely water-bearing is 0.50 meter-ohms; the connate water would occupy about 0.10 of the pore volume (Eq. 5). However, if the observed value on the log, 65 meter-ohms, were used without correcting for the borehole, the connate water would be calculated to occupy 0.09 of the pore volume. Therefore, although the effect of the borehole size and mud resistivity on the observed resistivity readings may be appreciable, the resultant effect on the calculated connate-water content of the sand is not important.

When the thickness of the formation is very large in comparison with the electrode spacing, there will, of course, be no correction to make for the thickness of the layer. However, when the thickness of the formation approaches the electrode spacing, the observed resistivity may be very different from the true value. Table 2 shows approximately what the third curve (long normal) of the Gulf Coast would read for certain bed thicknesses and resistivities. It is assumed that large shale bodies are present above and below the beds, at the same time neglecting the presence of the borehole and again assuming point electrodes.

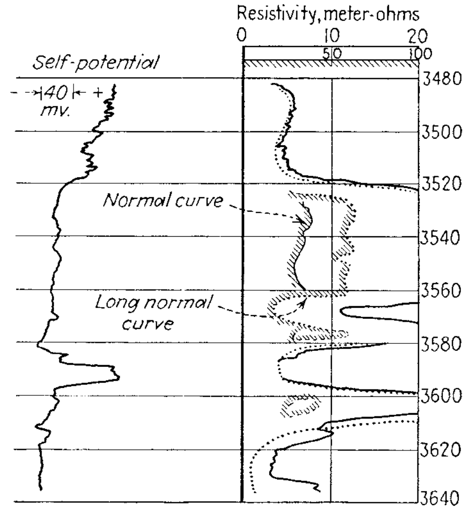

FIG. 4.—ELECTRICAL LOG OF AN EAST TEXAS WELL.
Diameter of hole, 7⅞ in.; mud resistivity, 3.4 at 85°F.; bottom-hole temperature, approximately 135°F.

Tables 1 and 2 assume ideal conditions, so if the sand is not uniform, or if invasion affects the third curve, the observed resistivity values may deviate farther from the true value. The magnitude of the influencing factors, of course, will limit the usefulness of the observed resistivity value recorded on the log. Invasion of the mud filtrate is probably the most serious factor; however, as previously mentioned, it can often be controlled by conditioning the mud flush for low filtrate loss.

Fig. 4 shows a log of an East Texas well. The observed resistivity on the long normal curve for the interval 3530 to 3560 ft. is 62 meter-ohms, or, from Table 1, approximately 50 meter-ohms after correcting for the borehole. In this instance the mud resistivity at the bottom-hole temperature of 135°F. is approximately 2.2 meter-ohms.

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The interval is thick enough so that there should be no appreciable effect due to electrode spacing. The formation is more or less a clean friable sandstone, so Eq. 5 can

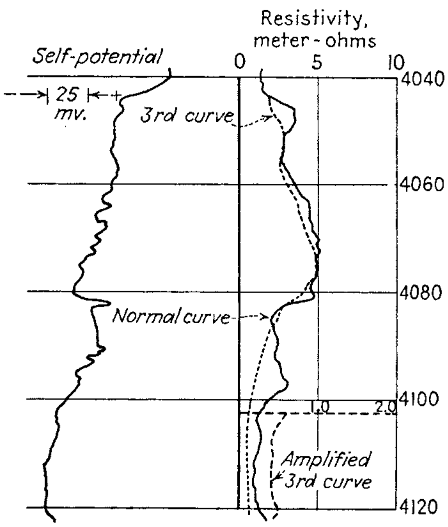

FIG. 5.—ELECTRICAL LOG OF A SAND IN EAST WHITE POINT FIELD, TEXAS.
Diameter of hole, 7⅞ in.; mud resistivity, 1.7 at 80°F.; bottom-hole temperature, 138°F.

be used to approximate the connate-water content. The formation resistivity factor for this sand is approximately 15, using Eq. 2 where $\theta = 0.25$ and $m = 1.8$. The resistivity of the formation water by actual measurement is 0.075 meter-ohms at a bottom-hole temperature of 135°F. Therefore, from Eq. 1, R_o for this sand is $15 \times 0.075 = 1.1$ meter-ohms. This value checks reasonably well with the value recorded at 3623 to 3638 ft. on this log as well as on the many logs from this pool where the Woodbine sand is water-bearing; i.e., 0.9 to 1.5 meter-ohms. The close check obtained between the calculated and recorded resistivity of the water sand indicates that invasion is not seriously affecting the third curve. Solving Eq. 5, the connate water of the zone 3530 to 3560 ft. occupies approximately $\sqrt{\frac{1.1}{50}} = 0.15$ of the pore volume. The accepted value assigned for the connate-water content of the East Texas reservoir is 17 per cent.

An electrical log of a sand in the East White Point field, Texas, is shown in Fig. 5. The observed resistivity at 4075 ft. is approximately 5 meter-ohms. The value of F for this sand by laboratory determination is 6. The sand is loosely consolidated, having 32 per cent porosity average. The resistivity of the formation water by direct measurement is 0.063 meter-ohms at the bottom-hole temperature of 138°F. Therefore, $R_o = 6 \times 0.063$ or 0.38 meter-ohms. This checks well with the value obtained by the electrical log between the depths of 4100 and 4120 ft., which is 0.40 (see amplified third curve). Therefore, invasion probably is not seriously affecting the third curve. From Tables 1 and 2 it appears that the borehole and electrode spacing do not seriously affect the observed resistivity at 4075 ft. The connate water is approximately $\sqrt{\frac{0.38}{5.0}}$, or 0.27.

Other uses of the empirical relations may have occurred to the reader. One would be the possibility of approximating the maximum resistivity that the invaded zone could reach (when formation water has a greater salinity than borehole mud) by Eq. 1, where R_w would now be the resistivity of the mud filtrate at the temperature of the formation and F the resistivity factor of the formation near the borehole. By knowing the maximum value of resistivity that the invaded zone could reach, the limits of usefulness of the log could be better judged. For example, assume that a porous sand having an F factor of less than 15 was under consideration. If the mud filtrate resistivity were 0.5 meter-ohms, the resistivity of the invaded zone, if completely flushed, would be $15 \times 0.5 = 7.5$. Thus the observed resistivity values of this sand up to approximately 7.5 meter-ohms could be due to invasion.

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Acknowledgment

Cooperation of the Shell Oil Co., Inc., and permission to publish this paper are gratefully acknowledged. The resistivity measurements on the numerous cores were performed under the supervision of S. H. Rockwood and J. H. McQuown, of the Shell Production Laboratories.

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DISCUSSION

(H. F. Beardmore presiding)

S. W. Wilcox,* Tulsa, Okla.—This paper recalls some of my own observations on the correlation of the electrical resistance of earth materials with their other physical properties. While Geophysical Engineer for the Department of Highways, of the State of Minnesota, from 1933 until 1936, I was primarily engaged in conducting earth-resistivity surveys prospecting for and exploring sand and gravel deposits. This work was done by two field parties using equipment of the Gish-Rooney type, and was carried out in every part of the state, both winter and summer.

In brief, when a sand or gravel prospect was discovered, in any way, it was detailed by the resistivity survey to outline its extent and to locate test holes for field and laboratory sample analysis. This survey consisted of a grid of "steptraverses" of one or more electrode separations, and for each an "iso-ohm," or equal resistance contour plan map, was drawn.

Several thousand earth-resistivity readings were taken over more than one hundred prospects. In some instances the test pitting was started before the completion of electrical survey and their findings were soon available for checking any suspected correlation theory and confirming what subsurface factors were being measured and how effectively.

From accepted earth-resistivity theory, it follows that within a definite sphere surrounding the electrodes the apparent resistance measurement is uniquely determined from the specific resistance and position of each and all of the particles making up the sphere. Any rational interpretation of these apparent resistance measurements is possible only for the simplest combinations of particles and their specific resistances. Fortunately, soils, subsoils and subsurface rocks, with their embodied fluids and gases, vary greatly in this property among themselves. For example, clay appears to have an average specific resistance of approximately 50 to 150 foot-ohms, whereas for sand and gravel the specific resistance is roughly from 2000 to 5000 foot-ohms. The important feature is the great absolute differences in resistance, consequently a resistance profile across a buried lens of sand or gravel surrounded by clay produces a striking response.

In spite of the amount of control available and the freedom for selecting various electrode intervals, no reliable quantitative predictions could be made that were not related to boundary surfaces. The probable depth to the first discontinuity—namely, the clay-sand contact—could be determined fairly accurately if the thickness of the sand body was considerable. When the depth to the sand was known from independent data, or could be assumed to be constant, it was possible to predict its thickness. If both were known, a good guess might be made regarding the depth to the water table; and, in addition, if all these were known, a surmise could be made about the quality of the sand; i.e., whether it contained organic material or was weathered. Perhaps if the degrees of control were sufficient the porosity of the sand, its grain size, or even its temperature might be predicted.

I observed that few of these variables, even the ones that generally contribute to the bulk of the readings, could be quantitatively separated without additional independent data; therefore my interpretation was necessarily empirical and based on experience. Fortunately, in sand and gravel prospecting the economically most important factors contribute their effects in the same direction. A high apparent resistance indicates either a thin body of highly resistant gravel near the surface, or a thicker one overlain with more clay stripping. Clean gravel is more resistant than weathered, and hard gravel more so than soft.

* Seismograph Service Corporation.

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In practical terms, I found that an apparent resistance reading of 500 foot-ohms for a 20-ft. electrode separation recorded over ground or glacial moraines of southern Minnesota reliably suggested a deposit of sand or gravel worth further investigation. As a matter of record, prospecting in the part of the state where these materials are very scarce, less than 3 per cent of the test holes located on the geophysical information failed to yield granular materials of commercial quality and quantity for at least highway subgrade treatment. Varying the electrode interval gave additional confirmation as to the thickness of the deposit and very little else.

In connection with our field work, we made extensive laboratory studies, attempting to work out the relation between the moisture content of sand and gravel and its specific resistance. These apparently simple experiments were not of much help in clearing up my field interpretations. Several variables were very hard to control in the laboratory.

The analogy between this type of earth-resistivity mapping and electrologging is close. The first measures electrical impedance along a surface generally parallel to the bedding planes; the latter, up a borehole more or less perpendicular to them. The same general limitations and possibilities appear to be common to both methods. Obviously, controls for checking are easier to obtain for plan mapping than for well logging within the depth of effective penetration.

My interpretation problems appeared to be essentially similar to those of electrical well logging where the operator, after observing the character of the resistance and the self-potential curves, tells his client whether pipe should be set. The accuracy of his prediction is based largely on experience and not on slide-rule calculations.

Mr. Archie's paper suggests an experimental attack for expanding and improving the interpretation technique of electrical well logging. Any contribution of this nature that increases its effectiveness is of great value to the petroleum industry. I offer my own experiences and observations to emphasize that he has tackled a difficult research problem and wish him luck.

Dr. A. G. Loomis,* Emeryville, Calif.—In the laboratory, we take into account the variations in measured resistivities of sands and tap water by finding out the cause of the variations in resistivity. That is, if the tap water itself varied from day to day, its electrolyte content must vary from day to day and chemical analysis would indicate the change. If sands did not give consistent resistivity readings, the character of the sands (in other words, the formation resistivity factor) probably changed or the kind and amount of water contained in the sand must have varied.

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BAKER, E.T., 1979

STRATIGRAPHIC AND HYDRGEOLOGIC FRAMEWORK

OF PART OF THE COASTAL PLAIN OF TEXAS

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

STRATIGRAPHIC AND HYDROGEOLOGIC FRAMEWORK OF PART OF THE COASTAL PLAIN OF TEXAS

By

E. T. Baker, Jr.

Open-File Report 77-712

Prepared in cooperation with
the Texas Water Development Board

March 1978

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STRATIGRAPHIC AND HYDROGEOLOGIC FRAMEWORK OF PART OF THE COASTAL PLAIN OF TEXAS

By

E. T. Baker, Jr.

ABSTRACT

The subsurface delineation of hydrogeologic units of Miocene and younger age and stratigraphic units of Paleocene to Holocene age establishes an interrelationship of these units Statewide across much of the Coastal Plain of Texas. The 11 dip sections and 1 strike section, which extend from the land surface to 7,600 feet (2,316 meters) below sea level, provide continuity of correlation from the outcrop to the relatively deep subsurface. Sand containing water with less than 3,000 milligrams per liter of dissolved solids, which is shown on the sections, serves as an index of water availability of this quality.

INTRODUCTION

This report has been prepared to illustrate the stratigraphic and hydrogeologic framework of a part of the Coastal Plain of Texas from the Sabine River to the Rio Grande. It is the outgrowth of a project that has as its ultimate objective the construction of a digital ground-water flow model, if feasible or desirable, of at least a part of the Miocene aquifers in the Gulf Coastal Plain of Texas. The model would serve as a tool for planning the development of the ground-water supplies. Work on the project is being done by the U.S. Geological Survey in cooperation with the Texas Water Development Board.

During the course of delineating the Miocene aquifers, which is basic to the design and development of the model, the scope of the study was broadened to include delineations of other hydrogeologic units, as well as delineations of stratigraphic units. As a result, units ranging in age from Paleocene to Holocene were delineated (table 1). A relationship of stratigraphic units to designated hydrogeologic units was thus established Statewide.

Eleven dip sections and one strike section are included in this report. The dip sections are spaced about 50 miles (80 km) apart with the most easterly one being near the Sabine River and the most southerly one being near the Rio Grande. Each dip section is about 100 miles (161 km) long and extends from near the coastline to short distances inland from the outcrop of the oldest Miocene formation--the Catahoula Tuff or Sandstone. The strike section, which is about 500 miles (804 km) long (in three segments), extends from the Sabine River to the Rio Grande and joins the dip sections at common control points. This section is from 50-75 miles (80-121 km) inland from the Gulf of Mexico and is essentially parallel to the coastline. The location of the sections and the Catahoula outcrop are shown on figure 1.

The sections extend from outcrops at the land surface to maximum depths of 7,600 feet (2,316 m) below sea level. Selected faunal occurrences, where known or inferred by correlation from nearby well logs, are included. The extent of sand that contains water having less than 3,000 mg/L (milligrams per liter) of dissolved solids was estimated from the electrical characteristics shown by the logs. This information is included on all of the sections.

Although faulting is common in the Coastal Plain and is complex in some areas, all faults have been omitted from the sections to maintain continuity of the stratigraphic and hydrogeologic boundaries. The disadvantage of such omission is, of course, the representation of an unrealistic and simplistic picture of unbroken stata with uninterrupted boundaries. In reality, many of the faults have not only broken the hydraulic continuity of the strata but more importantly have become barriers to fluid flow or conduits for cross-formational flow. The sections are presented in this report as figures 2-15.

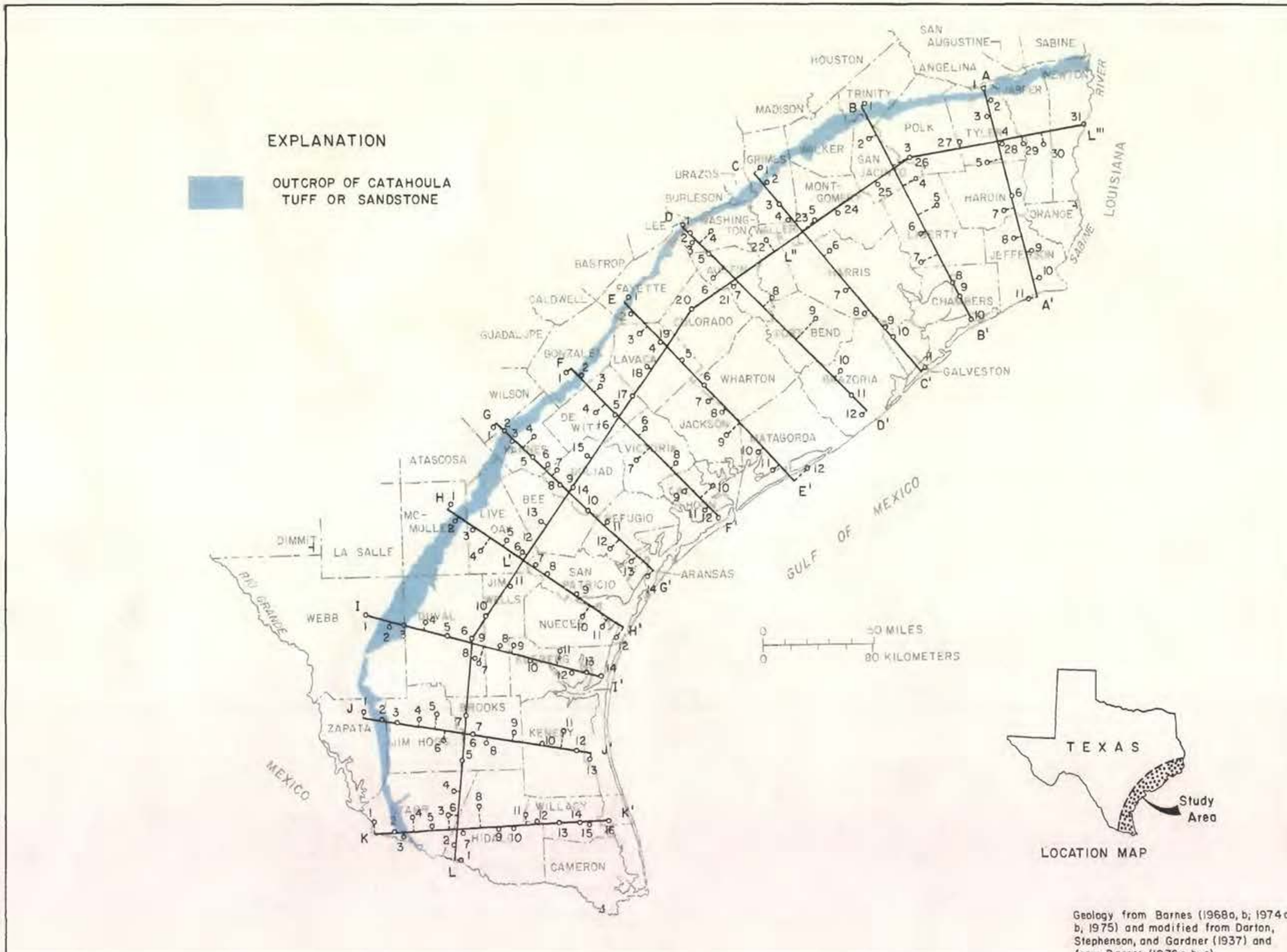

FIGURE 1.-Index map showing location of sections

77-712

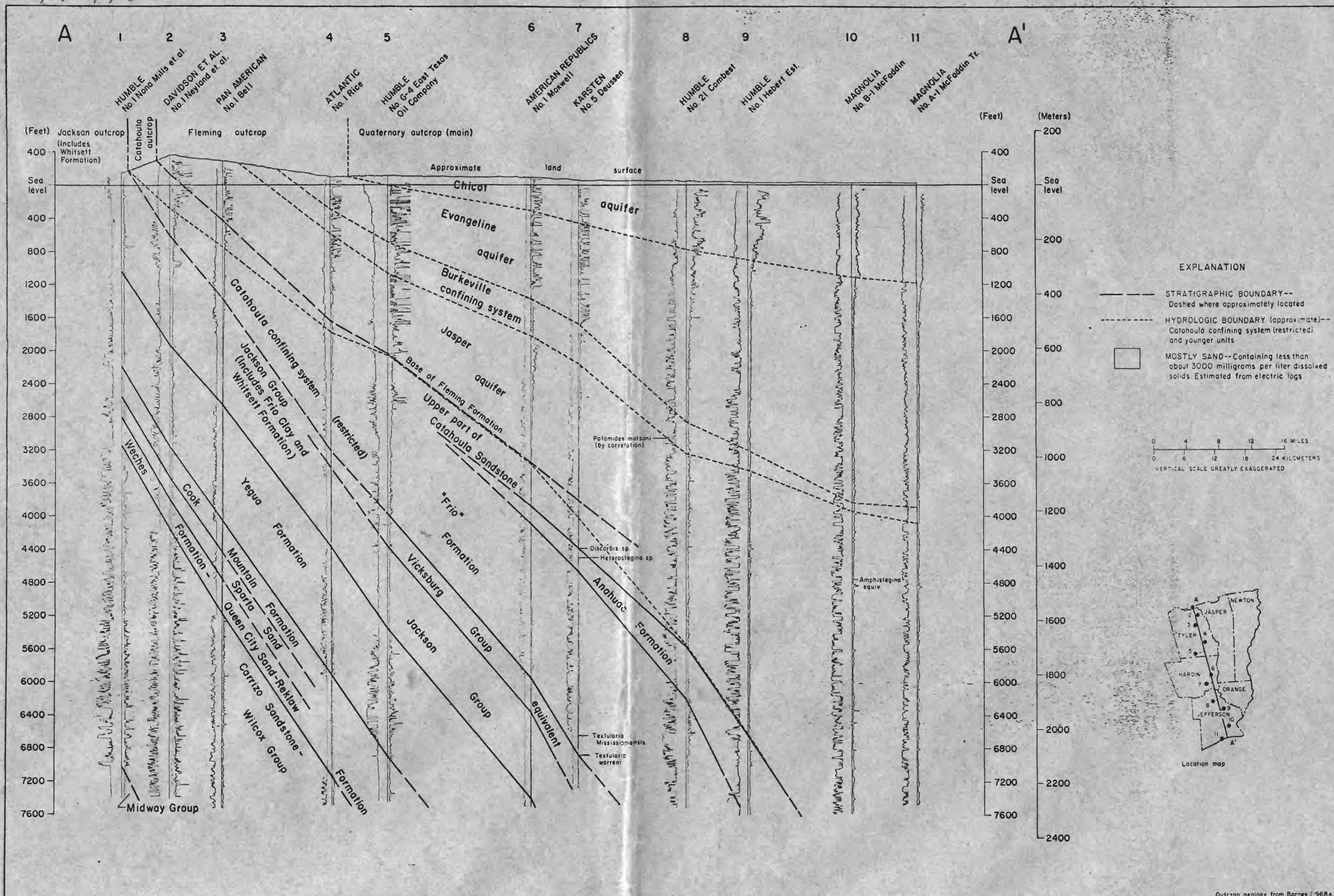

FIGURE 2.-Stratigraphic and hydrogeologic section A-A'

77-712

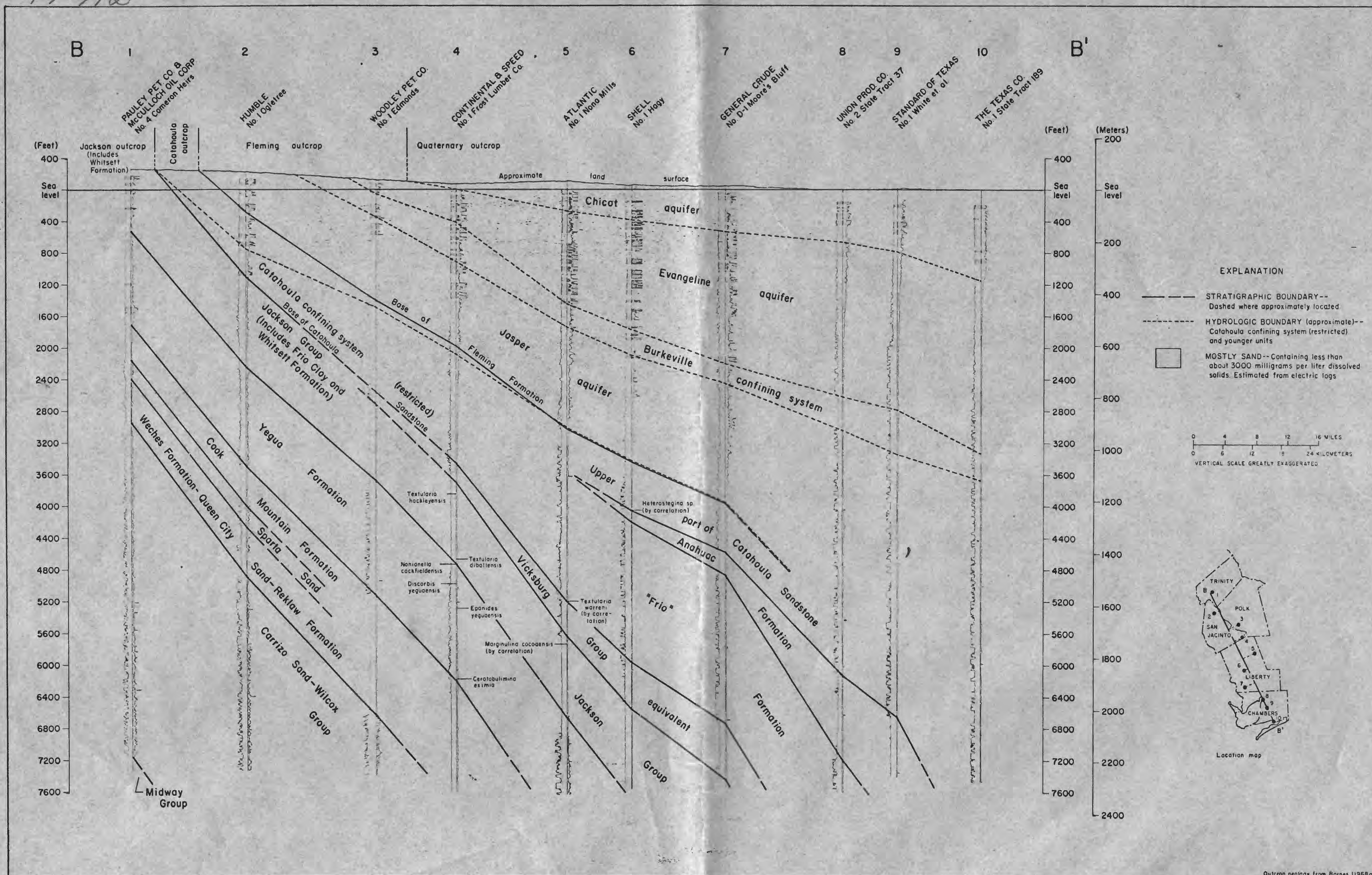

FIGURE 3.-Stratigraphic and hydrogeologic section B-B'

5

77-712

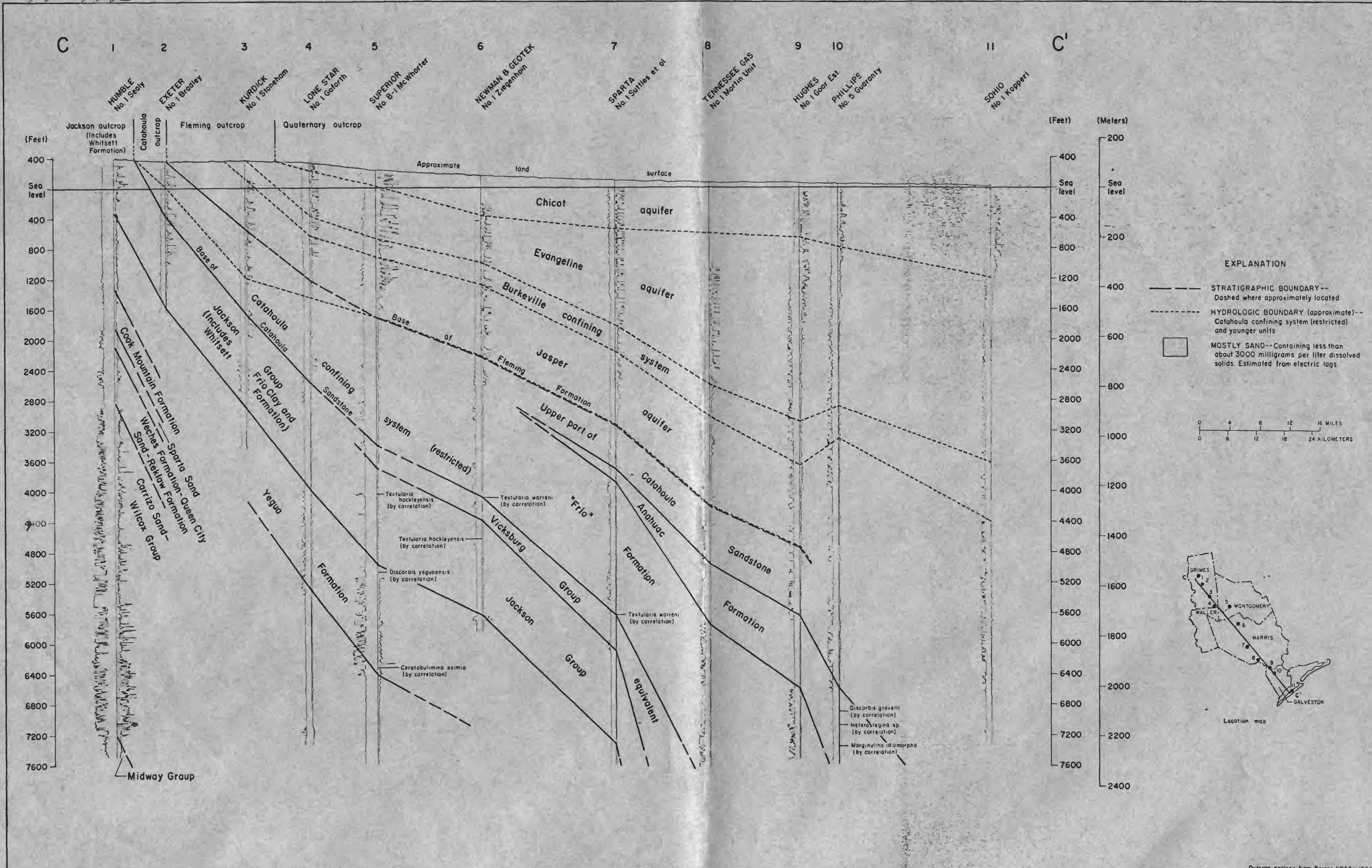

FIGURE 4.-Stratigraphic and hydrogeologic section C-C'

6

77-712

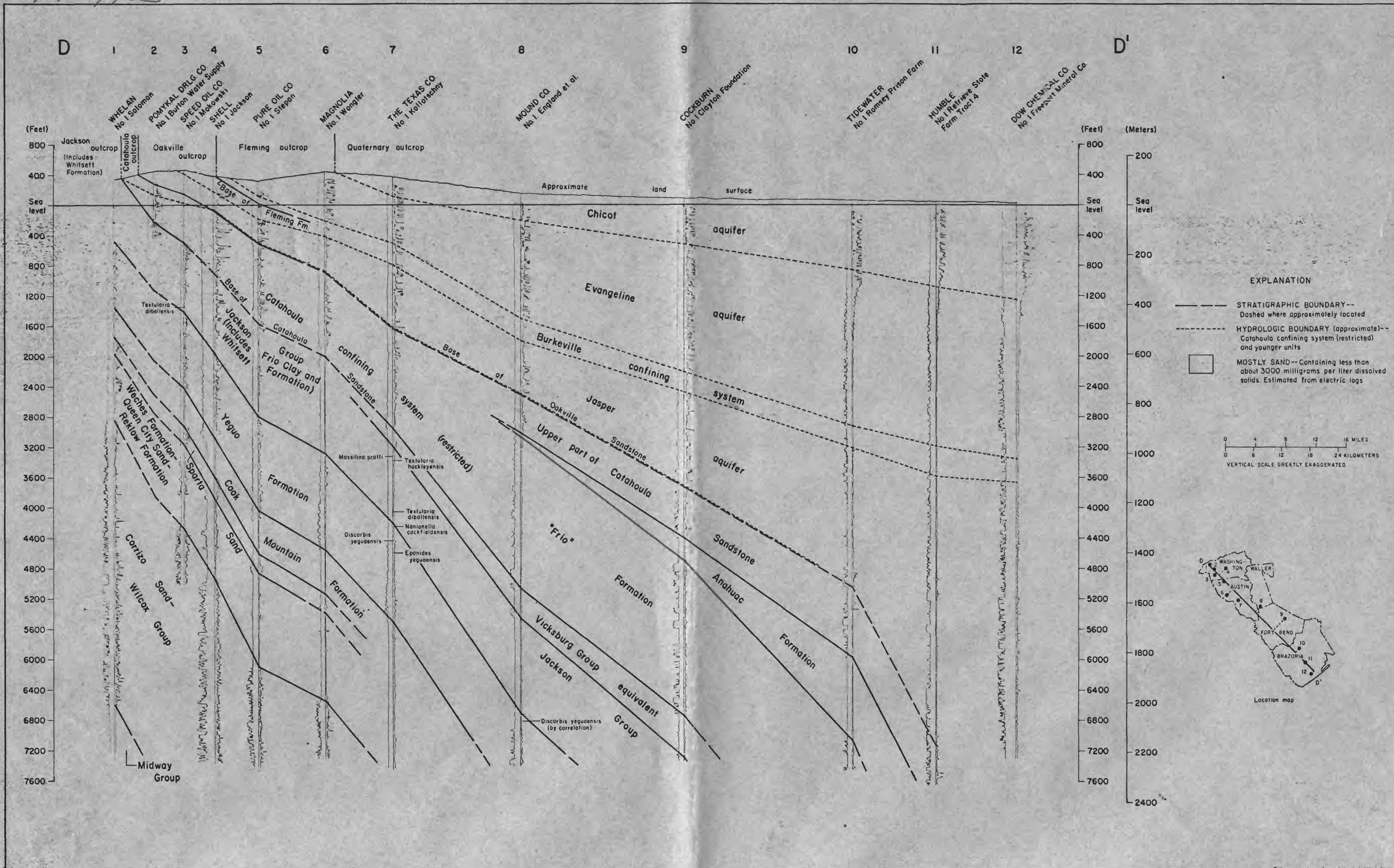

FIGURE 5.-Stratigraphic and hydrogeologic section D-D'

77-712

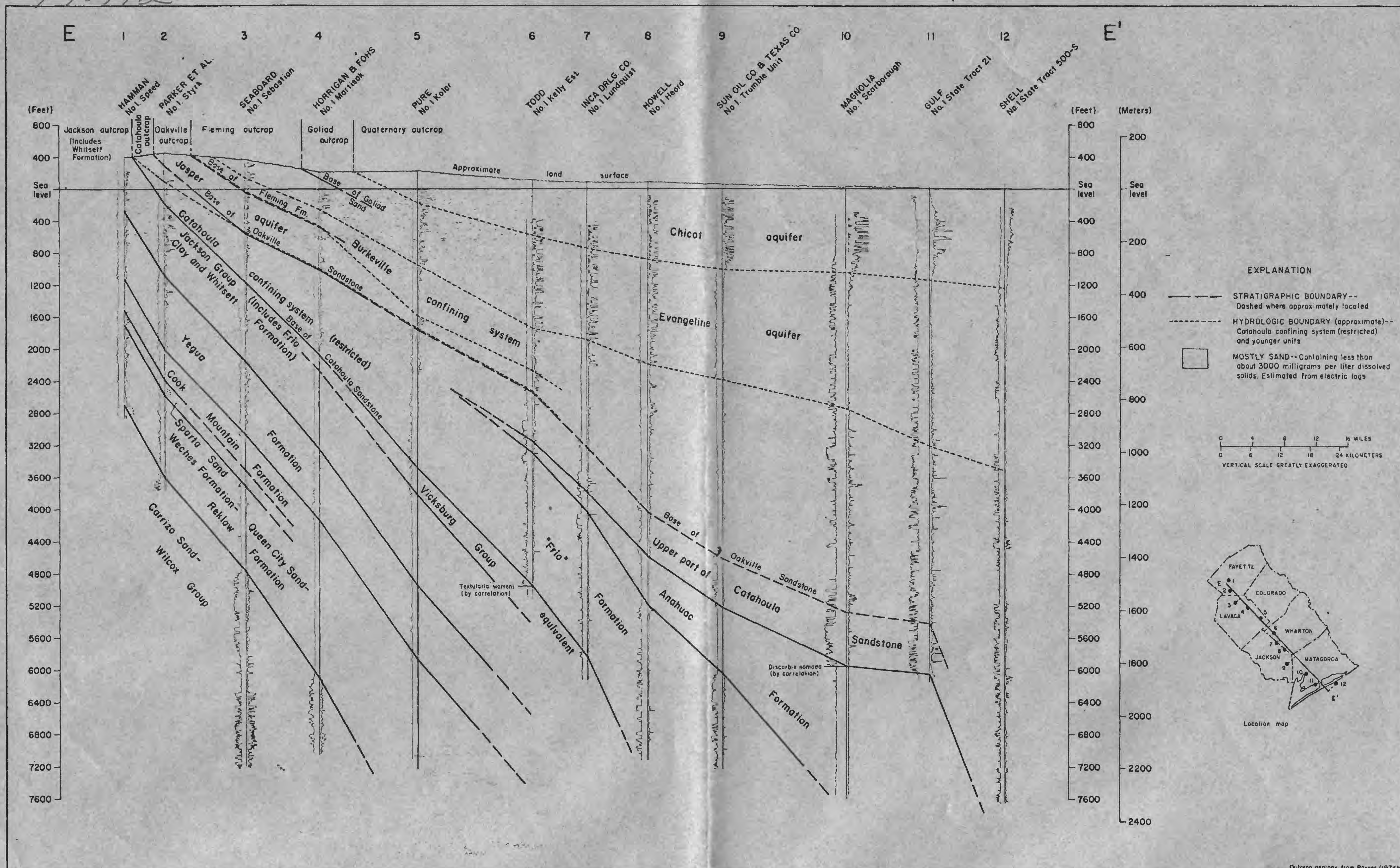

FIGURE 6.-Stratigraphic and hydrogeologic section E-E'

77-718

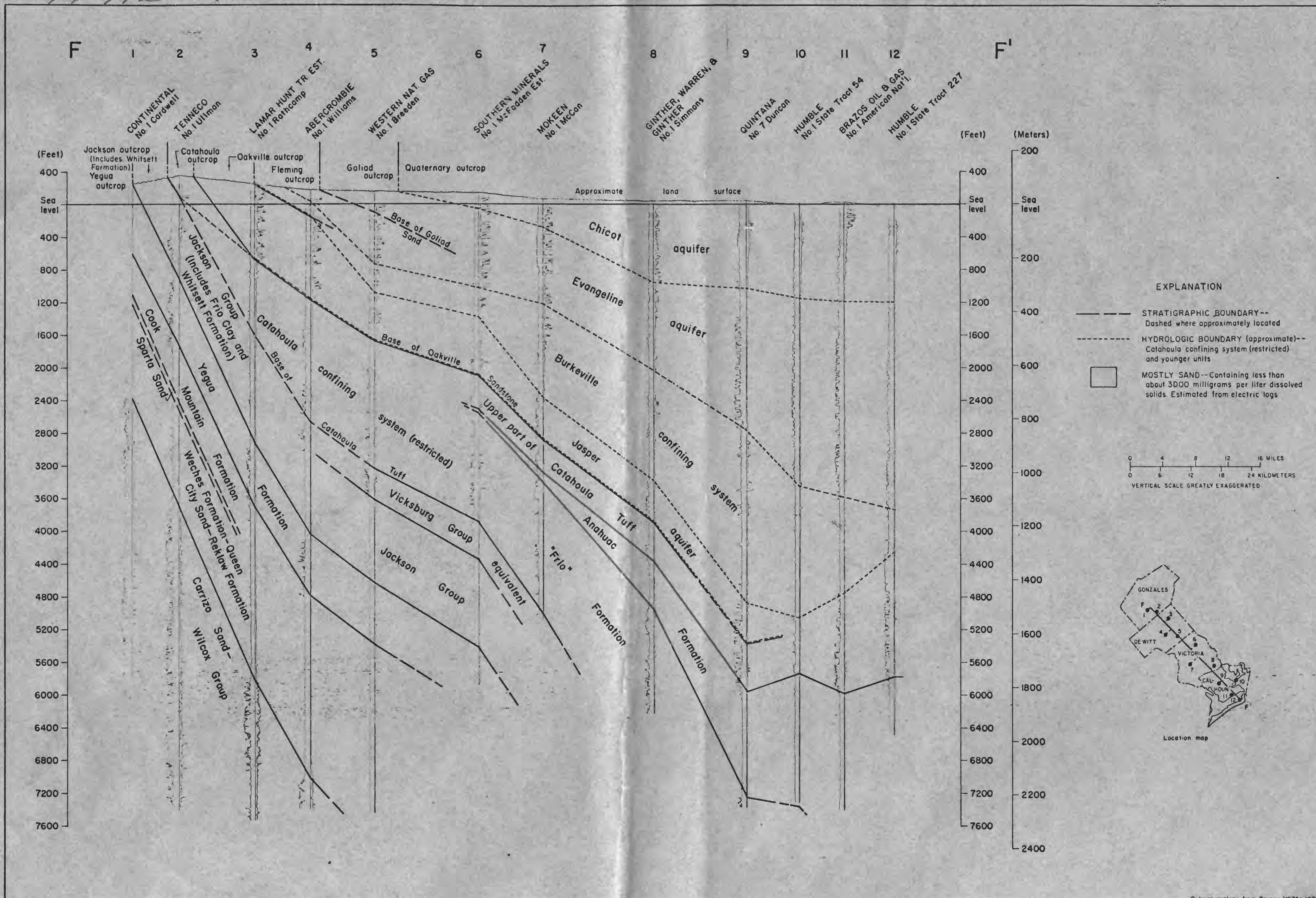

FIGURE 7.-Stratigraphic and hydrogeologic section F-F'

77-712

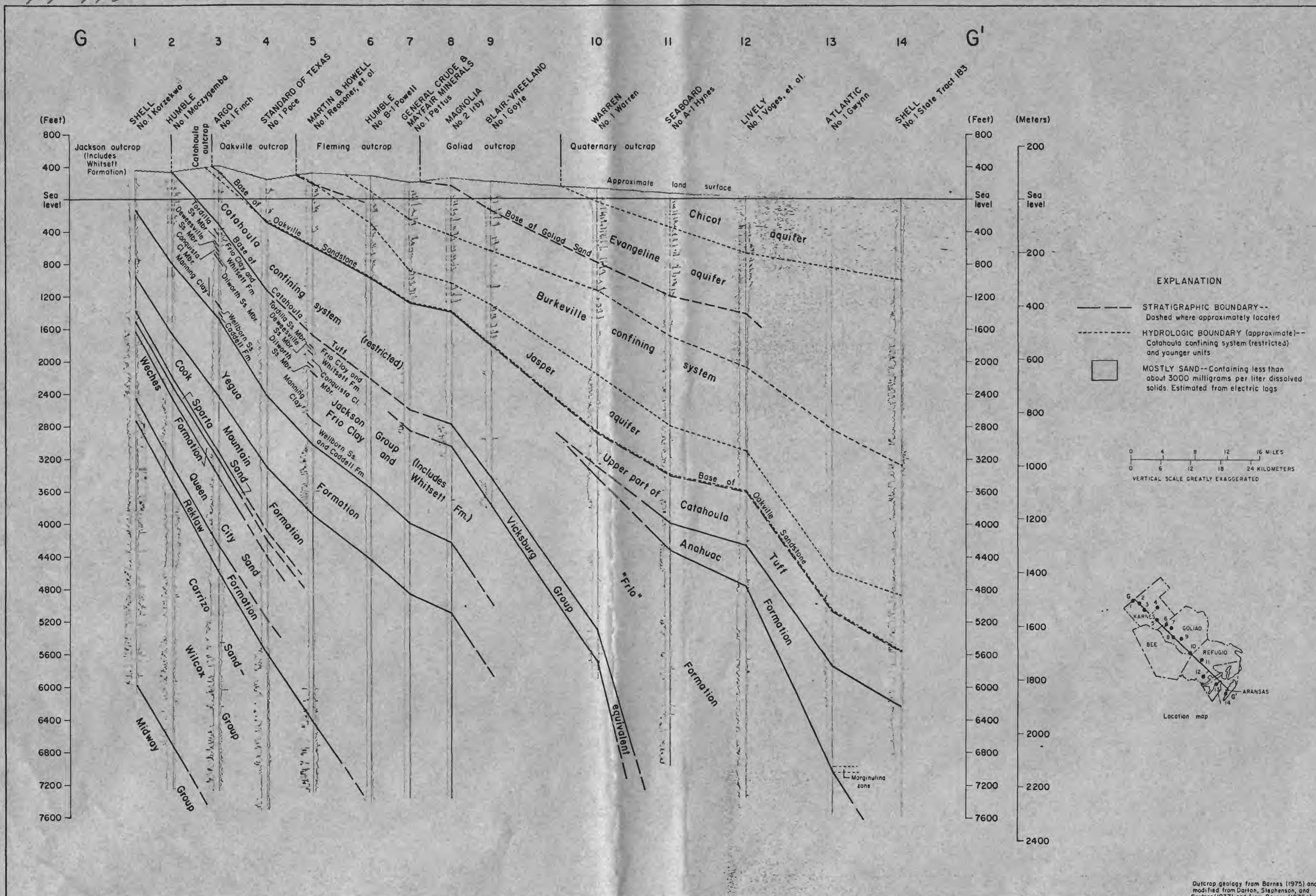

FIGURE 8.-Stratigraphic and hydrogeologic section G-G'

77-712

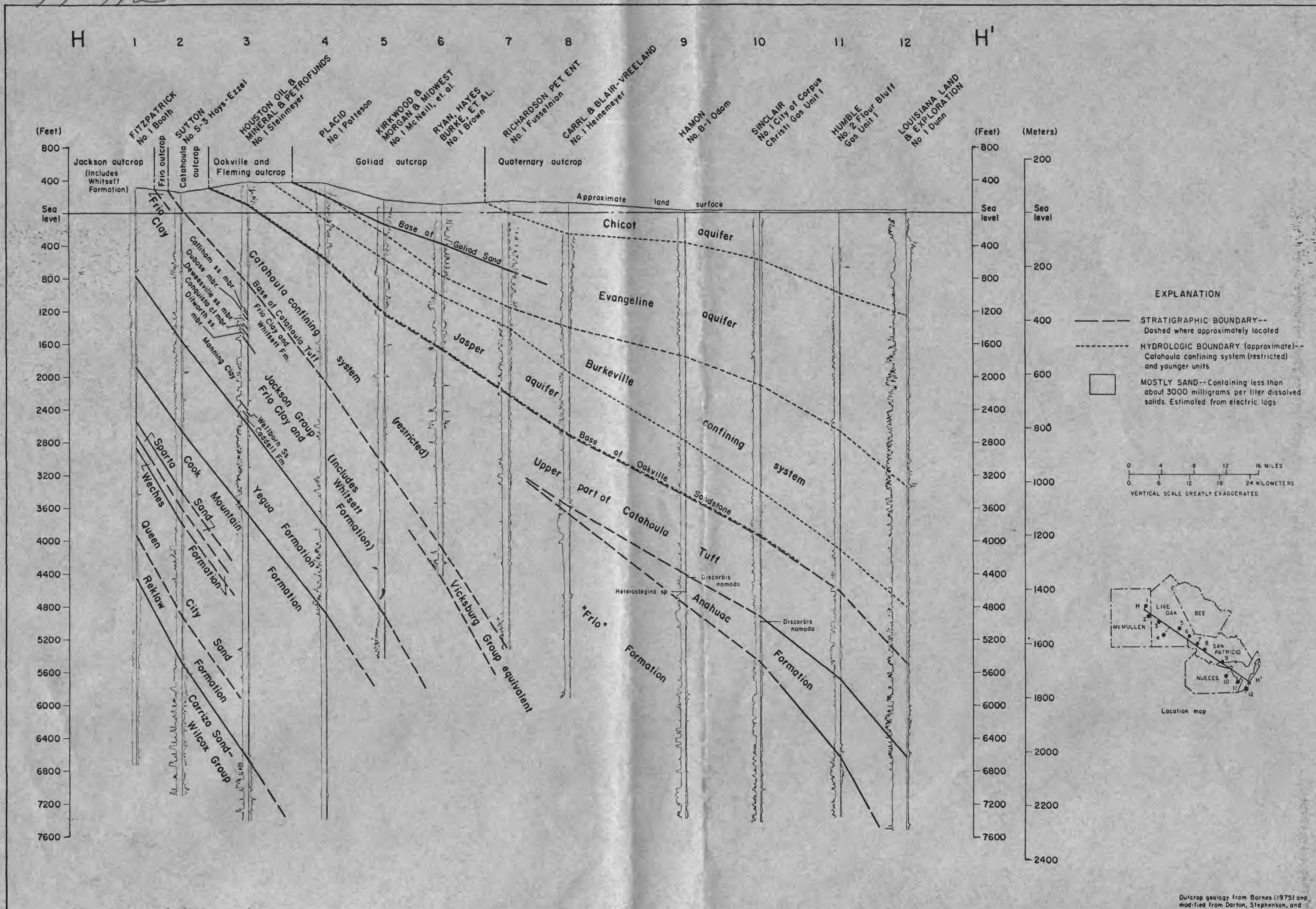

FIGURE 9.-Stratigraphic and hydrogeologic section H-H'

77-712

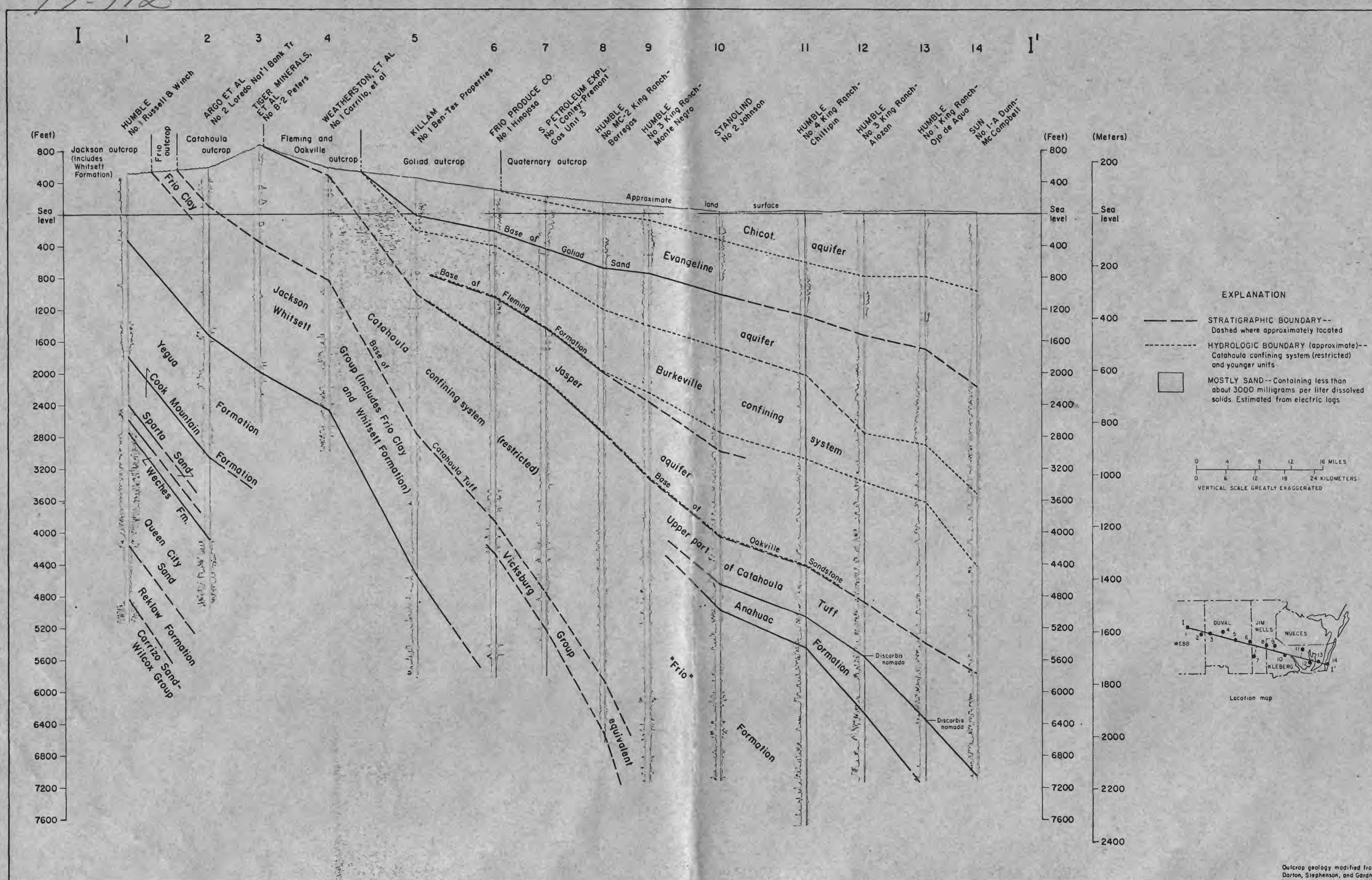

FIGURE 10.-Stratigraphic and hydrogeologic section I-I'

77-712

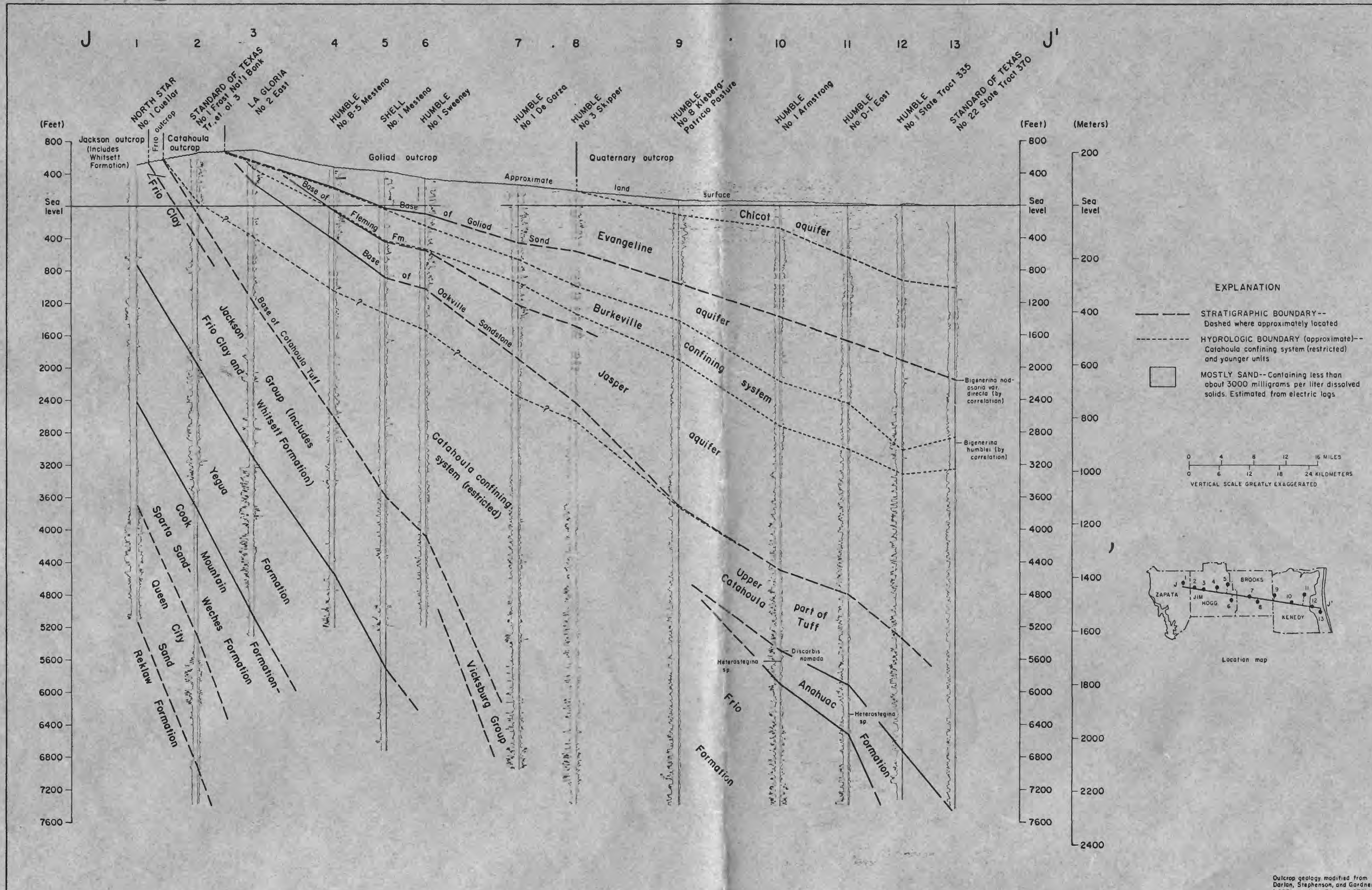

FIGURE 11.-Stratigraphic and hydrogeologic section J-J'

77-712

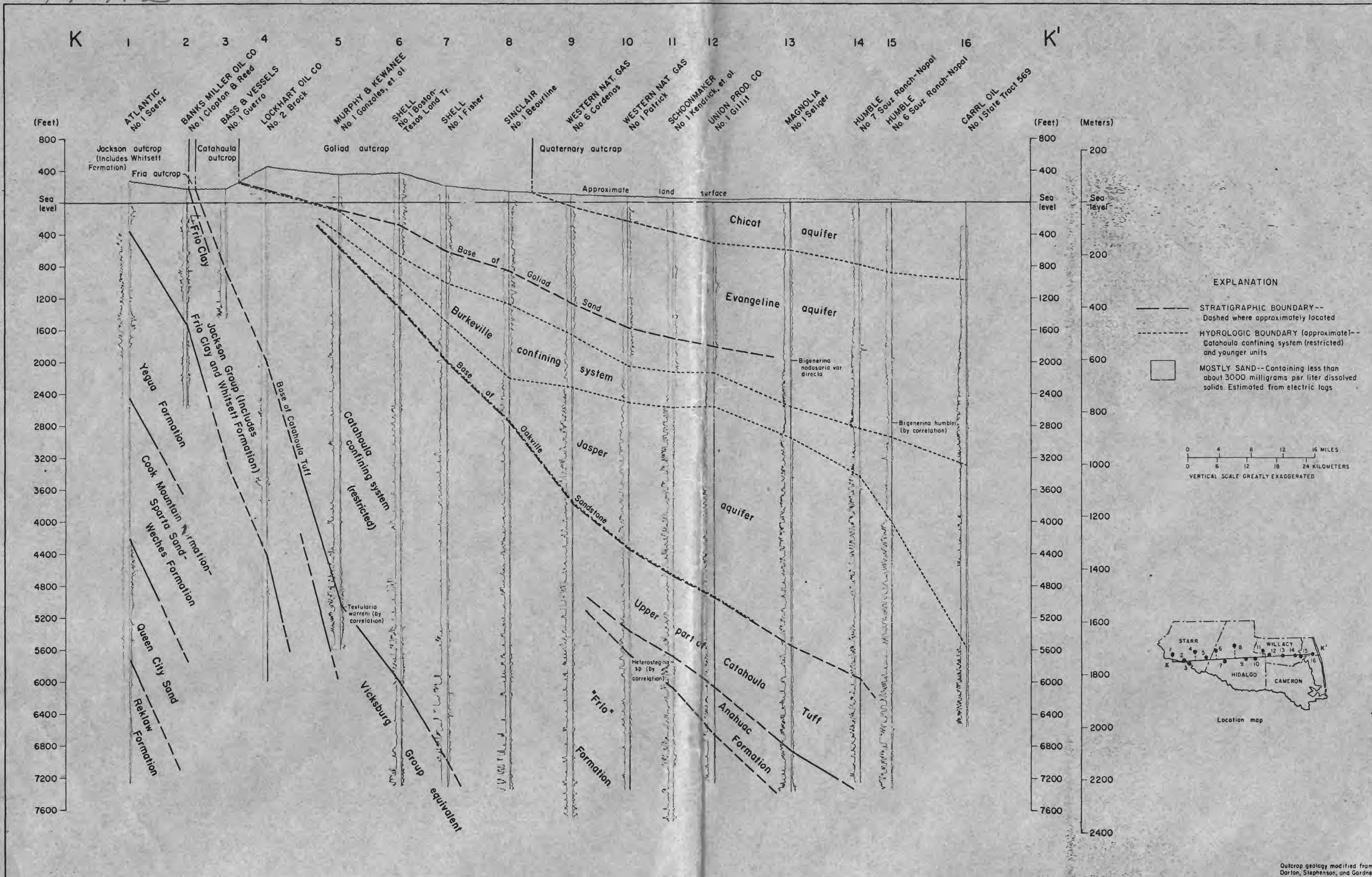

FIGURE 12.-Stratigraphic and hydrogeologic section K-K'

77-712

77-712

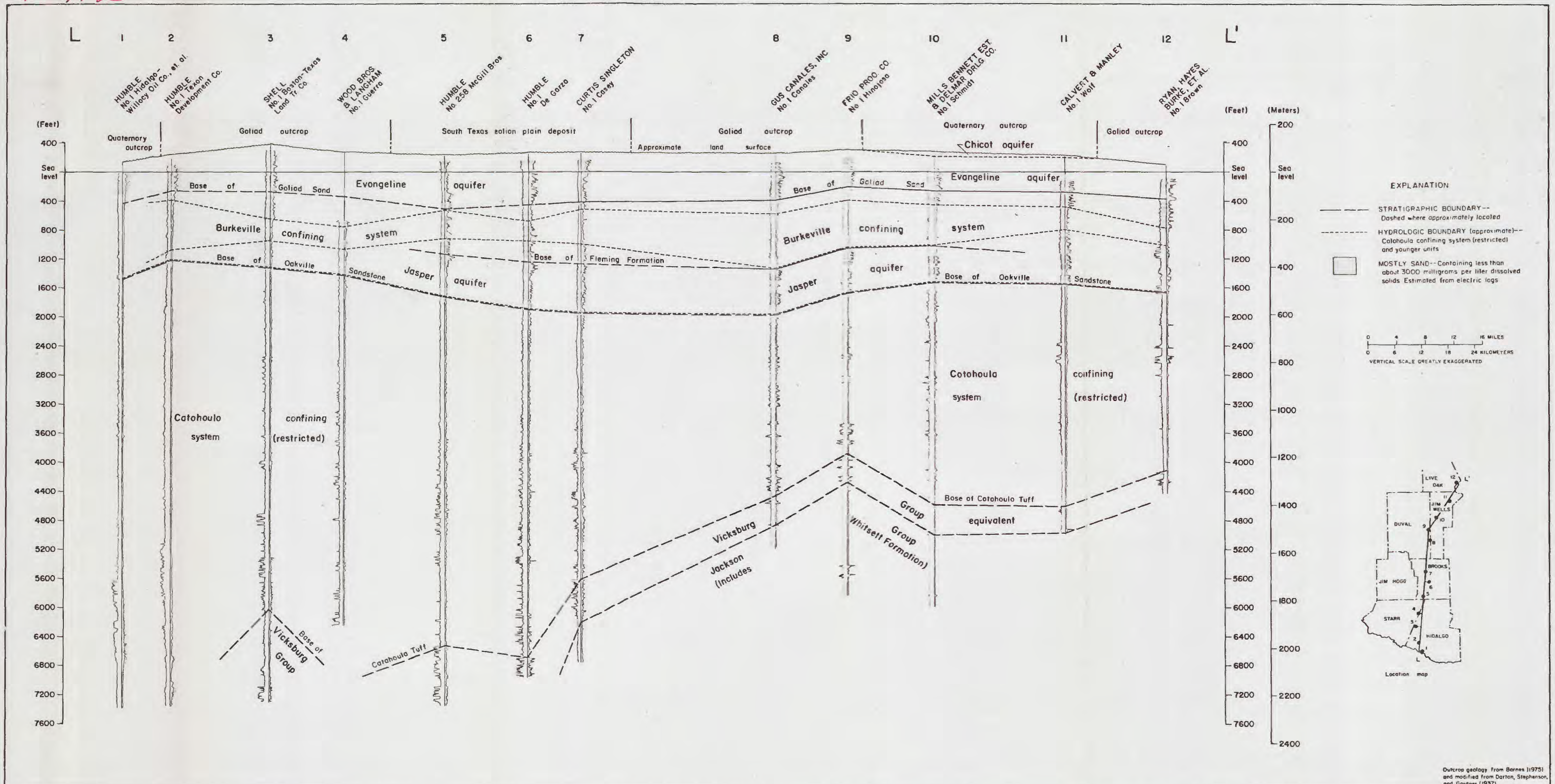

FIGURE 13.-Stratigraphic and hydrogeologic section L-L'

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77-712

FIGURE 14.-Stratigraphic and hydrogeologic section L'-L"

77-712

77-712

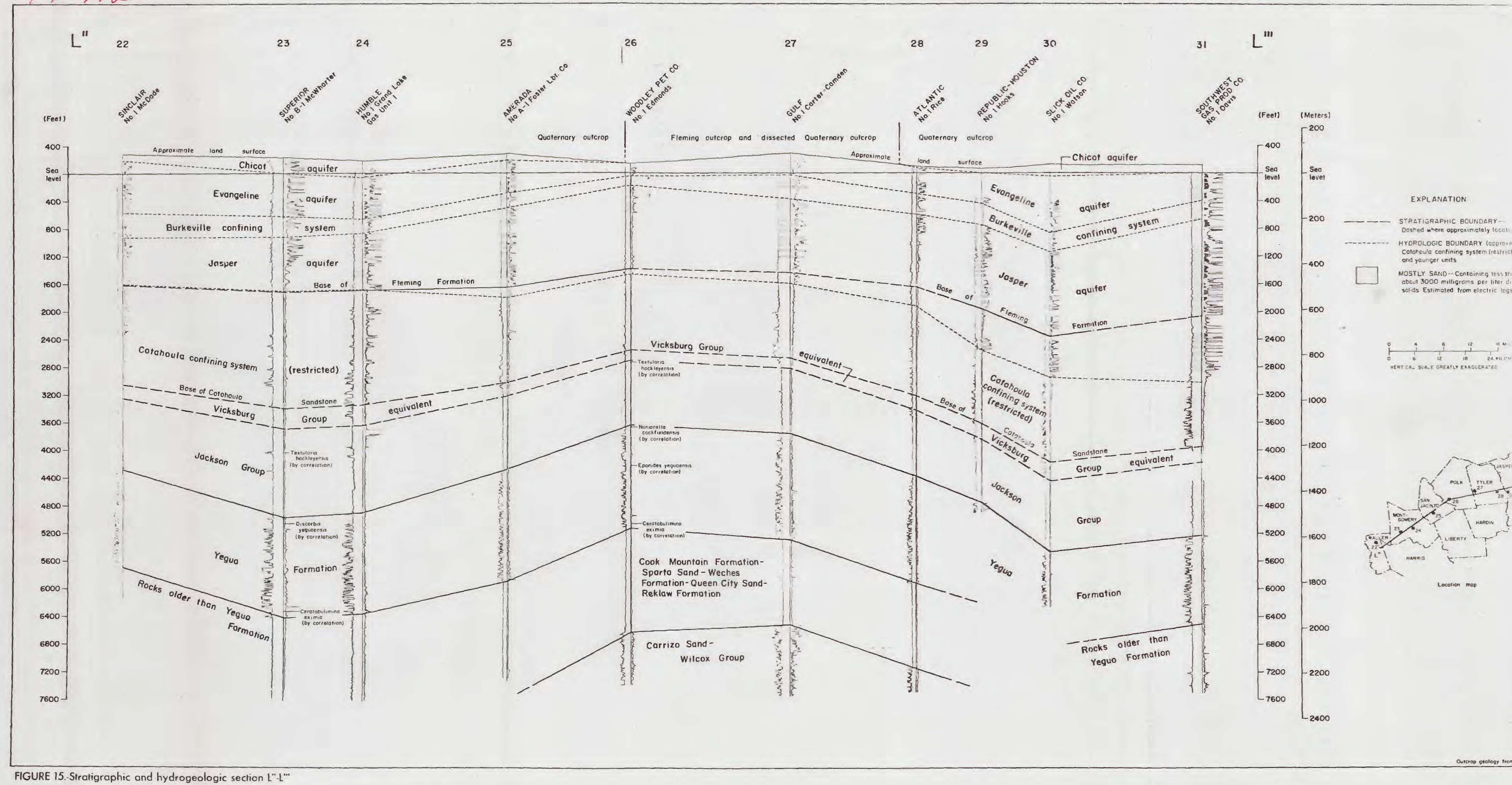

FIGURE 15.-Stratigraphic and hydrogeologic section L''-L'''

Table 1.--Stratigraphic and Hydrogeologic Framework of Part of the Coastal Plain of Texas

Era	System	Series	Stratigraphic Units			Hydrogeologic Units	Selected Faunal Markers	Remarks
CENOZOIC	Quaternary	Holocene	Alluvium			Chicot aquifer		Quaternary System undifferentiated on sections.
		Pleistocene	Beaumont Clay					
			Montgomery Formation					
			Bentley Formation					
			Willis Sand					
	Tertiary	Pliocene	Goliad Sand			Evangeline aquifer		Goliad Sand overlapped east of Lavaca County.
		Miocene	Fleming Formation			Burkeville confining system	Potamides matsoni Bigenerina nodosaria var. directa Bigenerina humblei Amphistegina sp.	
			Oakville Sandstone					Oakville Sandstone included in Fleming Formation east of Washington County.
			Surface	Catahoula Tuff or Sandstone	Subsurface: Upper part of Catahoula Tuff or Sandstone	Jasper aquifer		Catahoula Tuff designated as Catahoula Sandstone east of Lavaca County.
		? ?			Anahuac Formation	Catahoula confining system (restricted)	Discorbis nomada Discorbis gravelli Heterostegina sp. Marginulina idiomorpha	Anahuac and "Frio" Formations may be Oligocene in age.
					"Frio" Formation		Textularia mississippiensis	
		Oligocene(?)	Surface Frio Clay		Subsurface Vicksburg Group equivalent	Not discussed as hydrologic units in this report.	Textularia warreni	Frio Clay overlapped or not recognized on surface east of Live Oak County.
		? ?	Jackson Group	Whitsett Formation	Fashing Clay Member			Indicated members of Whitsett Formation apply to south-central Texas. Whitsett Formation east of Karnes County may be, in part or in whole, Oligocene in age.
					Calliham Sandstone Member or Tordilla Sandstone Member			
					Dubose Member		Marginulina cocoaensis	
					Deweesville Sandstone Member			
					Conquista Clay Member		Textularia hockleyensis	
					Dilworth Sandstone Member		Massilina pratti	
		Eocene		Manning Clay				
				Wellborn Sandstone			Textularia dibollensis	
				Caddell Formation				
			Claiborne Group	Yegua Formation			Nonionella cockfieldensis	
				Cook Mountain Formation			Discorbis yeguaensis	
				Sparta Sand			Eponides yeguaensis	
				Weches Formation			Ceratobulimina eximia	
				Queen City Sand				
				Reklaw Formation				
				Carrizo Sand				
		Paleocene	Wilcox Group					
			Midway Group					

Acknowledgments

The author wishes to express his appreciation to C. W. Holcomb (Exxon Co., USA), C. B. Phillips (Mobil Oil Corp.), and G. C. Hardin, Jr. (Ashland Exploration Co.) of Houston, Texas; J. G. Klatt (Mobil Oil Corp.) and J. C. Wyeth (Continental Oil Co.) of Corpus Christi, Texas; H. C. Hixson (Mobil Oil Corp.) of Denver, Colorado; and D. C. Bebout (Bureau of Economic Geology, University of Texas at Austin), for discussing correlation problems. Their assistance does not necessarily constitute an endorsement of the views expressed by the author in this report. The assistance of V. E. Barnes (Bureau of Economic Geology, University of Texas at Austin), who provided unpublished geologic maps of south Texas areas; of R. H. Wallace, Jr., J. B. Wesselman, and R. E. Taylor (U.S. Geological Survey) of Bay St. Louis, Mississippi; of P. H. Jones (Dept. of Geology, Louisiana State University), Baton Rouge, Louisiana, who provided log data, is also appreciated. D. G. Jorgensen (U.S. Geological Survey) of Lawrence, Kansas (formerly of Houston, Texas) and W. R. Meyer and W. M. Sandeen (U.S. Geological Survey) of Houston, Texas, delineated the Chicot and Evangeline aquifers on the sections. Their contribution is gratefully acknowledged. Geologic sections and type logs of oil fields including faunal occurrences by the Houston Geological Society (1954, 1962), the Corpus Christi Geological Society (1954, 1955, 1967, 1972), and the South Texas Geological Society (1962, 1967) were extensively utilized as aids in identifying deep subsurface formations. The geologic sections of Eargle, Dickinson, and Davis (1975) served to identify near-surface formations in parts of south Texas.

Metric Conversions

For those readers interested in using the metric system, the metric equivalents of English units of measurements are given in parentheses. The English units used in this report have been converted to metric units by the following factors:

From		Multiply by	To obtain	
Unit	Abbreviation		Unit	Abbreviation
feet	--	0.3048	meters	m
miles	--	1.609	kilometers	km

STRATIGRAPHIC FRAMEWORK

General Features of Deposition and Correlation Problems

Cenozoic sediments that underlie the Coastal Plain of Texas are tens of thousands of feet thick at the coastline. These clastic sediments of sand, silt, and clay represent depositional environments ranging from non-marine at the outcrops of most units to marine where the units may carry a distinctive suite of fossils. Oscillations of ancient seas and changes in amount and source of sediments that were deposited caused facies changes downdip and along strike. For example, a time-stratigraphic unit having age equivalency may consist of sand in one area, sandy clay in a second area, and clay in a third area. Subsidence of the basin of deposition and rising of the land surface caused the stratigraphic units to thicken Gulfward. Growth faults (faults that were more or less continuously active) greatly increased the thickness of some stratigraphic units in short distances. All of these factors contributed to the heterogeneity of the units from place to place, which in turn makes correlation difficult.

Stratigraphic Units

In the discussion to follow, emphasis will be placed on stratigraphic units that are designated in this report as Miocene in age. Many of the correlation problems of the Cenozoic deposits involve these units to a large degree. Also the main thrust of this report is directed at the Miocene in keeping with the ultimate objective of modeling the flow in the Miocene aquifers.

The stratigraphic nomenclature used in this report was determined from several sources and may not necessarily follow the usage of the U.S. Geological Survey.

Pre-Miocene

Delineation of most of the pre-Miocene units of Cenozoic age present relatively few problems of significance. This is especially true of the pre-Jackson units (Midway Group to Yegua Formation). The top of the Carrizo Sand of the Claiborne Group (included with the underlying Wilcox Group on the sections) can be easily delineated, which makes the position of the unit ummistakable in the subsurface. From about the Sabine River to the San Marcos Arch (section F-F', fig. 7, is centered over this structural feature) the top of the Carrizo-Wilcox is about 3,000 feet (914 m) beneath the landward edge of the Catahoula outcrop. Southward from the San Marcos Arch into the Rio Grande Embayment of south Texas, its position steadily increases in depth to more than 7,000 feet (2,134 m) at the western end of section K-K' (fig. 12).

Facies changes occur downdip in the Sparta and Queen City Sands of the Claiborne Group, and where these units grade into clay, delineation on a time-stratigraphic basis is virtually impossible from electrical-log interpretation. The same problem affects the Yegua Formation of the Claiborne Group, although the Yegua remains sandy for greater distances downdip. It can be delineated by lithology on most of the sections in this report. Also, the presence of important faunal markers such as *Nonionella cockfieldensis* and *Ceratobulimina eximia* aid in locating the approximate top and base, respectively, of the Yegua, regardless of its lithology.

The delineation of the Jackson Group is significant in establishing the framework for the Miocene units. This is because the outcropping Frio Clay of Oligocene(?) age of south Texas is completely overlapped in Live Oak County by the Miocene Catahoula (or is not recognized on the surface east of this area). The overlap places the Catahoula in contact with part of the Whitsett Formation, the uppermost formation of the Jackson Group in this area. East of the overlap to the Sabine River, careful attention was required to properly separate on the sections the tuffaceous sand and clay interbeds of the Whitsett from the tuffaceous sand and clay interbeds of the overlying Catahoula. From Live Oak County southward, the outcropping Frio Clay separates the Whitsett Formation from the Catahoula Tuff.

The age of the Whitsett, although shown in table 1 as Eocene in south-central Texas, may be at least in part Oligocene in the eastern part of the State. Eargle, Dickinson, and Davis (1975) consider the Whitsett to be Eocene at least from central Karnes County to southern McMullen County. Barnes (1975) likewise considers the Whitsett to be unquestionably Eocene no farther east than central Karnes County. From this area to the Sabine River, Dr. V. E. Barnes (written commun., Apr. 5, 1971) states that the Whitsett may "climb timewise eastward" and be largely Oligocene in east Texas; that the Nash Creek Formation of Louisiana, which is considered to be largely Oligocene, is equivalent to the Whitsett as mapped in Texas near the Sabine River; and the Oligocene vertebrates, which Dr. J. A. Wilson (Dept. of Geologic Sciences, University of Texas at Austin) collected from the Whitsett in Washington County, show that this formation is at least part Oligocene at that site. Because of the probability that the Whitsett is Oligocene, in part or in whole in much of the area, the delineation of the Eocene Jackson Group is shown on the sections to include the Whitsett Formation.

The Frio Clay of Oligocene(?) age has been a controversial unit for decades. Geologists still do not agree on its subsurface equivalents or if it is even a separate stratigraphic unit from the Catahoula. The fact that many geologists have mapped the unit from Live Oak County to the Rio Grande lends support to the existence of the Frio Clay as a formation. The Geologic Atlas of Texas (Barnes, 1976a,b,c) shows that the Frio is mapped separately as a distinct formation from its overlap in Live Oak County to southern Webb County; from there to the Rio Grande, the Frio is undifferentiated from the Catahoula. The Frio outcrop that was used for control at the surface on the dip sections H-H' to K-K' (figs. 9-12) was modified from Darton, Stephenson, and Gardner (1937) and from Barnes (1976a,b,c). East of the overlap in Live Oak County the Frio is presumed to be present in the shallow subsurface beneath the Catahoula with the erosional edge probably only a few miles downdip from the edge of the Catahoula outcrop.

The Frio Clay at the surface has been interpreted by the author to be, at least in part, the nonmarine time-equivalent of the subsurface Vicksburg Group--a marine biostratigraphic unit of Oligocene age that crops out east of the Sabine River and is characterized by the foraminifer Textularia warreni. The relationship is supported by Deussen and Owen (1939, p. 1630) and by the Houston Geological Society (1954). The Vicksburg equivalent east of Karnes County may also be at least a partial time-equivalent of the Whitsett, whose probable Oligocene age in this area may, in itself, indicate an equivalency. Ellisor (1944, fig. 1, and p. 1365) supports this probability and illustrates the relationship in a geologic section. Additionally, this probability is supported by the apparent correlation of the outcrop of the Vicksburg Group in Louisiana near the Sabine River as shown on the geologic map of Louisiana (Wallace, 1946) with the outcrop of the Whitsett Formation as shown on the Geologic Atlas of Texas (Barnes, 1968b). This relationship may be inferred on the dip sections from A-A' to at least F-F' (figs. 2-7) where the Vicksburg equivalent, if projected to the outcrop, would intersect the outcropping Whitsett.

Miocene

The stratigraphic framework of the units that are designated in this report as Miocene in age is complex and controversial, perhaps more so than any other Cenozoic units. Geologists do not agree which units on the surface or in the subsurface are Miocene nor do they agree as to the relationship of the surface and subsurface units. The correct relationship may never be determined because faunal markers, which exist in places in the subsurface, do not extend to the outcrop; and the heterogeneity of the sediments does not facilitate electrical-log correlations.

The outcropping stratigraphic units that are assigned to the Miocene in this report are, from oldest to youngest, the Catahoula Tuff or Sandstone, Oakville Sandstone, and Fleming Formation. The "Frio" Formation, Anahuac Formation, and a unit that is referred to in this report as the upper part of the Catahoula Tuff or Sandstone are assigned by the author as possible downdip equivalents of the surface Catahoula although the Anahuac and "Frio" Formations may be Oligocene in age. Table 1 and the dip sections (figs. 2-12) illustrate this relationship.

The outcrop of the Catahoula, a pyroclastic and tuffaceous unit, has been mapped independently by various geologists with little modification from the Sabine River to the Rio Grande. Darton, Stephenson, and Gardner (1937) modified the unit's name from Catahoula Tuff to Catahoula Sandstone east of Lavaca County where the formation becomes more sandy.

It may be seen on the sections that the thickness of the surface Catahoula increases downdip at a large rate in the subsurface to eventually include, when the Anahuac Formation is reached, the "Frio" Formation which underlies the Anahuac, the Anahuac, and the upper Catahoula unit. Deussen and Owen (1939, figs. 5, 6, p. 1632, and table 1), in a study of the surface and subsurface formations in two typical sections of the Texas Coastal Plain (one in east Texas, the other in south Texas) agree with this relationship. They disagree, however, with these units being Miocene and assign them to the Oligocene. Some oil-company geologists consider the Anahuac and "Frio" as separate formations (unrelated to the Catahoula) in the subsurface and also assign them to the Oligocene. As a consequence of this usage, the upper Catahoula unit of this report is then usually referred to as "Miocene," which term is used instead of, or interchangeably with, Fleming. Holcomb (1964, fig. 2) in a study of the subsurface "Frio" Formation of south Texas places the "Frio" and Anahuac Formations, as well as the surface Catahoula in the Miocene, but does not admit to any Catahoula occurring above the Anahuac. He indicates that the "Fleming Formation" (Oakville Sandstone and Fleming Formation of this report) rests on the Anahuac. Dip sections, especially F-F', G-G', and H-H' (figs. 7-9), show unmistakably that the Catahoula-Oakville contact on the surface can be accurately traced far enough downdip by means of electrical logs to show that the clearly discernible contact is several hundred feet above the Anahuac. For this reason, the upper Catahoula unit above the Anahuac cannot be the Oakville. This contention is supported by Meyer (1939, p. 173) and by Lang and others (1950, plate 1).

The Anahuac Formation, despite the controversial attention it receives, is one of the most discernible formations in the subsurface. This marine biostratigraphic unit carries a rich microfauna of many tens of diagnostic species. These species are categorized into the Discorbis zone, Heterostegina zone, and Marginulina zone, from youngest to oldest. Only a few of the diagnostic species (table 1) are included with the dip sections in this report. The updip limit of the marine facies of the Anahuac ranges in depth from about 2,500 feet (762 m) below land surface in east Texas to about 4,000 feet (1,219 m) in the Rio Grande Embayment in south Texas. The unit is quite sandy south of San Patricio County (south of section H-H', fig. 9) to the Rio Grande in contrast to its shaly character eastward from San Patricio County to the Sabine River.

The Oakville Sandstone and Fleming Formation are composed almost entirely of terrigenous clastic sediments that form sand and clay interbeds. Both formations are basically rock-stratigraphic units that are distinguished and delineated on the basis of lithologic characteristics. Their boundaries in the Coastal Plain of Texas are discernible contacts in some areas and arbitrary ones within zones of lithologic gradation in other areas.

The Oakville Sandstone is most prominent on the surface and in the subsurface in the central part of the Coastal Plain. Here its predominantly sandy character is distinguished from the underlying tuffaceous Catahoula and overlying Fleming, which is composed of clay and slightly subordinate amounts of sand.

The Oakville on the surface has been mapped as a formation from about the Brazos River at the Washington-Grimes County line to central Duval County, where its outcrop is overlapped by the Goliad Sand and remains overlapped to the Rio Grande. Beneath this overlap, the Oakville apparently decreases in thickness or loses its predominance of sand or both. In either case, its position in the shallow subsurface in parts of the Rio Grande Embayment is questionable on dip sections I-I' and K-K' (figs. 10, 12). In the vicinity of the Brazos River, the Oakville grades eastward into the base of the Fleming Formation and loses its identity. The position of the base of the Oakville in the deeper parts of the subsurface has been delineated on some of the sections merely as an approximation.

The Fleming Formation, the uppermost unit of Miocene age in the Coastal Plain, has been mapped on the surface in Texas from the Sabine River to central Duval County. From here, like the Oakville, it is overlapped by the Goliad Sand and remains beneath the Goliad to the Rio Grande.

The Fleming is lithologically similar to the Oakville but can be easily separated from the Oakville in some places by its greater proportion of clay. Plummer (1932, p. 744, 747) described the Lagarto as consisting of 75 percent marl or clay, 15 percent sand, and 10 percent silt, with the clay beds being thicker and more massive and the sand beds being thinner and less massive than those of the Oakville. This description is reasonably accurate in some areas of the outcrop and shallow subsurface where the Fleming is separated from the Oakville. (See sections I-I', J-J', and L-L', figs. 10, 11, and 13.) In other areas, the Fleming on the outcrop and in the shallow subsurface contains a ratio of sand to clay that approximates that of the Oakville. Where the Fleming Formation is not separated from the Oakville and directly overlies the Catahoula, from about Grimes County to the Sabine River, the percentage of sand in the formation increases eastward. In Jasper and Newton Counties, the amount of sand in the section above the base of the Fleming greatly exceeds the amount of clay. This can be seen in wells 30 and 31 on strike section L"-L"' (fig. 15).

Delineation of the base of the Fleming from the surface to the deep subsurface has not been attempted on most of the sections because of complex facies changes. In southeast Texas on sections A-A', B-B', and C-C' (figs. 2-4) an approximate base of the Fleming is shown downdip to short distances beyond the pinchout of the Anahuac. The preponderance of sand above the Anahuac in this area, however, makes any delineation on the basis of electrical logs speculative. Deep wells near the coastline penetrate marine facies of the Fleming which carry a diagnostic fauna. Numerous species, which serve to identify the formation, have been described by Rainwater (1964). *Potamides matsoni*, *Amphistegina sp.*, *Bigenerina humblei*, and *Bigenerina nodosaria var. directa* are faunal markers indicated on some of the sections.

Post-Miocene

Delineation of the stratigraphic units of Pliocene, Pleistocene, and Holocene age has not been attempted. Correlation problems with most of these stratigraphic units are too numerous to solve by using only electrical logs. Delineation of the Pleistocene units--Willis Sand, Bentley Formation, Montgomery Formation, and Beaumont Clay--is exceedingly difficult due to the lithologic similarity of the sediments and lack of paleontological control. The contact at the surface of the basal Quaternary with the Goliad Sand or older units is, however, shown on the dip sections.

The Goliad Sand of Pliocene age overlies the Miocene units in the deep subsurface as well as in places on the surface. Except for a few isolated outcrops, it is otherwise entirely overlapped on the surface east of Lavaca County by Pleistocene deposits. Its inland extent beneath the overlap is presumed to be only several miles southeast from the most downdip exposures of the Fleming Formation. From Lavaca County to the Rio Grande, the width of the Goliad outcrop gradually increases because the Goliad progressively overlaps older units in the Rio Grande Embayment of south Texas.

The Goliad Sand can usually be identified on the surface and in the subsurface by a preponderance of sand except in the far eastern part of the State where sand predominates from the base of the Miocene to the surface. In this area, the identity of the Goliad cannot be established with certainty. Delineation of the base of the Goliad has been made, where outcrop control is available, on the strike and dip sections west of Colorado County. The base of the Goliad has been approximated at about 2,200 feet (671 m) below sea level near the coastline on sections I-I' and J-J' (figs. 10, 11).

HYDROGEOLOGIC FRAMEWORK

The following discussion is restricted to the hydrogeologic framework of five units--Catahoula confining system (restricted), Jasper aquifer, Burkeville confining system, Evangeline aquifer, and Chicot aquifer. A discussion of other hydrologic units of Cenozoic age is beyond the purpose and scope of this report.

The quality of the ground water that is indicated on the sections to be less than 3,000 mg/L of dissolved solids is referred to in this report as fresh to slightly saline water. This terminology follows the classification of Winslow and Kister (1956).

Catahoula Confining System (Restricted)

The Catahoula confining system (restricted) is treated in this report as a quasi-hydrologic unit with different boundaries in some areas than the stratigraphic unit of the same name. Its top (base of the Jasper aquifer) is delineated along lithologic boundaries that are time-stratigraphic in some places but that transgress time lines in other places. Its base, which coincides with the base of the stratigraphic unit, is delineated everywhere along time-stratigraphic boundaries that are independent of lithology. No attempt was made to establish a lithologic (hydrologic) base for the unit, which would have created a distinct hydrologic unit. Such effort would have involved a thorough hydrologic evaluation of pre-Miocene formations, which is beyond the scope of the project.

In many places, the Catahoula confining system (restricted) is identical to the stratigraphic unit, but there are notable exceptions. These departures of the hydrologic boundaries from the stratigraphic boundaries are most prominent in the eastern part of the Coastal Plain near the Sabine River (fig. 15), in places in south Texas (fig. 11), and in numerous places at the outcrop and in the shallow subsurface. In these places, the very sandy parts of the Catahoula Tuff or Sandstone (stratigraphic unit) that lie immediately below the Oakville Sandstone or Fleming Formation are included in the overlying Jasper aquifer. This leaves a lower section from 0 to 2,000 feet (610 m) or more in thickness that consists predominantly of clay or tuff with some interbedded sand to compose the Catahoula confining system (restricted). In most areas, this delineation creates a unit that is generally deficient in sand so as to preclude its classification in these areas as an aquifer. Thus in much of its subsurface extent, the Catahoula confining system (restricted) functions hydrologically as a confining layer that retards the interchange of water between the overlying Jasper aquifer and underlying aquifers.

The amount of clay and other fine-grained clastic material in the Catahoula confining system (restricted) generally increases downdip, until the Anahuac Formation is approached. Below this unit, the "Frio" Formation becomes characteristically sandy and contains highly saline water that extends to considerable depths.

Jasper Aquifer

The Jasper aquifer, which was named by Wesselman (1967) for the town of Jasper in Jasper County, Texas, has heretofore not been delineated farther west than Washington, Austin, and Fort Bend Counties. In this report, a delineation as far downdip as possible has been made of the Jasper from the Sabine River to the Rio Grande.

The configuration of the Jasper aquifer in the subsurface, as shown on the sections, is geometrically irregular. This irregularity is due to the fact that the delineation was necessarily made on the basis of the aquifer being a rock-stratigraphic unit. The hydrologic boundaries were defined by observable physical (lithologic) features rather than by inferred geologic history.

The configuration of the base and top of the Jasper transgresses stratigraphic boundaries along strike and downdip. The lower boundary of the aquifer coincides with the stratigraphic lower boundary of the Oakville or Fleming in some places. In other places the base of the Jasper lies within the Catahoula or coincides with the base of that unit. The top of the aquifer is within the Fleming Formation in places, follows the top of the Oakville Sandstone in other places, and is within the Oakville in still other places.

The Jasper ranges in thickness from as little as 200 feet (61 m) to about 3,200 feet (975 m). The maximum thickness occurs within the region of highly saline water in the aquifer. An average range in thickness of the aquifer within the zone of fresh to slightly saline water is from about 600 to 1,000 feet (183 to 305 m). In the eastern part of the Coastal Plain of Texas the Jasper contains a greater percentage of sand than in the southern part. At the Sabine River, the Jasper attains a thickness of 2,400 feet (732 m) in well 31 on section L"-L"' (fig. 15), where the aquifer is composed almost entirely of sand. Fresh to slightly saline water, as shown on section D-D' (fig. 5), occurs as deep as 3,000 feet (914 m) below sea level.

Delineation of the Jasper aquifer in Louisiana (Whitfield, 1975), in western Louisiana and eastern Texas (Turcan, Wesselman, and Kilburn, 1966), and in Jasper and Newton Counties, Texas (Wesselman, 1967) shows that the thickness of the Jasper at the Sabine River closely approximates that given by the author. For example, the author assigns a thickness of 2,400 feet (732 m) to the Jasper in well 31 on section L"-L"' (fig. 15), and the authors cited above show essentially the same thickness at the site. This agreement in aquifer thickness, however, is contrasted to different interpretations of the stratigraphic composition or age of the aquifer near the Sabine River. The authors cited above restrict the Jasper to a part of the Fleming Formation, whereas this paper redefines the Jasper at its type locality near the Sabine River to include the upper part of the Catahoula of Texas in addition to the lower part of the Fleming of Texas. (This redefinition applies only to the area of the type locality and is thus only locally valid. Elsewhere in the Coastal Plain of Texas the Jasper assumes a different stratigraphic makeup.)

The stratigraphic discrepancies at the Texas-Louisiana border are attributed to different interpretations of the surface geology at the State line. The Palestine quadrangle of the Geologic Atlas of Texas (Barnes, 1968b) shows the Catahoula outcrop to be about 6 miles (9.7 km) wide at the Sabine River, whereas Welch (1942) shows the outcrop in Louisiana to be about 1 mile (1.6 km) wide. A close comparison of the two geologic maps indicates that in Louisiana the Lena, Carnahan Bayou, and at least part of the Dough Hills Members of Fisk (1940) of the Fleming Formation of Kennedy (1892), in addition to the Catahoula of Welch (1942), are equivalent to the Catahoula of Texas. Wesselman (1967) assigned the Carnahan Bayou Member as the basal part of the Jasper, which is reasonable; but this member is Catahoula in age in Texas. As long as the discrepancy in geologic mapping is unresolved, subsurface correlations of the Catahoula-Fleming contact, as well as formation thicknesses, will continue to differ.

Burkeville Confining System

The Burkeville confining system, which was named by Wesselman (1967) for outcrops near the town of Burkeville in Newton County, Texas, is delineated on the sections from the Sabine River to near the Rio Grande. It separates the Jasper and Evangeline aquifers and serves to retard the interchange of water between the two aquifers.

The Burkeville has been mapped in this report as a rock-stratigraphic unit consisting predominantly of silt and clay. Boundaries were determined independently from time concepts although in some places the unit appears to possess approximately isochronous boundaries. In most places, however, this is not the case. For example, the entire thickness of sediment in the Burkeville confining system in some areas is younger than the entire thickness of sediment in the Burkeville in other places.

The configuration of the unit is highly irregular. Boundaries are not restricted to a single stratigraphic unit but transgress the Fleming-Oakville contact in many places. This is shown on sections D-D' to G-G' and J-J' (figs. 5-8 and 11). Where the Oakville Sandstone is present, the Burkeville crops out in the Fleming but dips gradually into the Oakville because of facies changes from sand to clay downdip.

The typical thickness of the Burkeville ranges from about 300 to 500 feet (91 to 152 m). However, thick sections of predominantly clay in Jackson and Calhoun Counties account for the Burkeville's gradual increase to its maximum thickness of more than 2,000 feet (610 m) as shown on section F-F' (fig. 7).

The Burkeville confining system should not be construed as a rock unit that is composed entirely of silt and clay. This is not typical of the unit, although examples of a predominance of silt and clay can be seen in some logs in sections H-H' and I-I' (figs. 9-10). In most places, the Burkeville is composed of many individual sand layers, which contain fresh to slightly saline water; but because of its relatively large percentage of silt and clay when compared to the underlying Jasper aquifer and overlying Evangeline, the Burkeville functions as a confining unit.

Evangeline Aquifer

The Evangeline aquifer, which was named and defined by Jones (Jones, Turcan, and Skibitzke, 1954) for a ground-water reservoir in southwestern Louisiana, has been mapped also in Texas, but heretofore has been delineated no farther west than Washington, Austin, Fort Bend, and Brazoria Counties. Its presence as an aquifer and its hydrologic boundaries to the west have been a matter of speculation. D. G. Jorgensen, W. R. Meyer, and W. H. Sandeen of the U.S. Geological Survey (written commun., March 1, 1976) recently refined the delineation of the aquifer in previously mapped areas and continued its delineation to the Rio Grande. The boundaries of the Evangeline as they appear on the sections in this report are their determinations.

The Evangeline aquifer has been delineated in this report essentially as a rock-stratigraphic unit. Although the aquifer is composed of at least the Goliad Sand, the lower boundary transgresses time lines to include sections of sand in the Fleming Formation. The base of the Goliad Sand at the outcrop coincides with the base of the Evangeline only in south Texas as shown in sections H-H' to K-K' (figs. 9-12). Elsewhere, the Evangeline at the surface includes about half of the Fleming outcrop. The upper boundary of the Evangeline probably follows closely the top of the Goliad Sand where present, although this relationship is somewhat speculative.

The Evangeline aquifer is typically wedge shaped and has a high sand-clay ratio. Individual sand beds are characteristically tens of feet thick. Near the outcrop, the aquifer ranges in thickness from 400 to 1,000 feet (122 to 305 m), but near the coastline, where the top of the aquifer is about 1,000 feet (305 m) deep, its thickness averages about 2,000 feet (610 m). The Evangeline is noted for its abundance of good quality ground water and is considered one of the most prolific aquifers in the Texas Coastal Plain. Fresh to slightly saline water in the aquifer, however, is shown to extend to the coastline only in section J-J' (fig. 11).

Chicot Aquifer

The Chicot aquifer, which was named and defined by Jones (Jones, Turcan, and Skibitzke, 1954) for a ground-water reservoir in southwestern Louisiana, is the youngest aquifer in the Coastal Plain of Texas. Over the years, the aquifer gradually was mapped westward from Louisiana into Texas where, heretofore, its most westerly mapped limit was Austin, Fort Bend, and Brazoria Counties. In this report, the delineation of the Chicot was refined in previously mapped areas and extended to near the Rio Grande by D. G. Jorgensen, W. R. Meyer, and W. M. Sandeen of the U.S. Geological Survey (written commun., March 1, 1976).

It is believed that the base of the Chicot in some areas has been delineated on the sections in this report as the base of the Pleistocene. Early work in southeast Texas indicates that the Chicot probably comprises the Willis Sand, Bentley Formation, Montgomery Formation, and Beaumont Clay of Pleistocene age and any overlying Holocene alluvium (table 1). The problem that arises in this regard is that the base of the Pleistocene is difficult to pick from electrical logs. Thus any delineation of the base of the Chicot in the subsurface as the base of the Pleistocene is automatically suspect. At the surface, the base of the Chicot on the sections has been picked at the most landward edge of the oldest undissected coastwise terrace of Quaternary age. In practice, the delineation of the Chicot in the subsurface, at least on the sections in southeast Texas, has been based on the presence of a higher sand-clay ratio in the Chicot than in the underlying Evangeline. In some places, a prominent clay layer was used as the boundary. Differences in hydraulic conductivity or water levels in some areas also served to differentiate the Chicot from the Evangeline.

The high percentage of sand in the Chicot in southeast Texas, where the aquifer is noted for its abundance of water, diminishes southwestward. Southwest of section G-G' (fig. 8) the higher clay content of the Chicot and the absence of fresh to slightly saline water in the unit is sharply contrasted with the underlying Evangeline aquifer that still retains relatively large amounts of sand and good quality water.

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DAVIS, K.E., 1986

FACTORS AFFECTING THE AREA OF REVIEW FOR HAZARDOUS WASTE DISPOSAL WELLS

PROCEEDINGS OF THE INTERNATIONAL SYMPOSIUM ON SUBSURFACE INJECTION OF LIQUID WASTES

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Published by

National Water Well Association
6375 Riverside Dr.
Dublin, OH 43017

Produced by

Water Well Journal Publishing Co.
6375 Riverside Dr.
Dublin, OH 43017

FACTORS EFFECTING THE AREA OF REVIEW

FOR HAZARDOUS WASTE DISPOSAL WELLS

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Abstract

The area of review, for a hazardous waste disposal well, is defined as the radial distance from the receiving well in which the pressure, caused by injection, increases sufficiently to possibly cause migration of fluids into useable sources of drinking water (USDW). Among the potential conduits for fluid migration from the disposal formation are improperly plugged well bores, channeling behind the casing of the injection w faulted formations, solution channels, naturally fractured formation facies pinch-outs. Usually faults, solution channels and most other naturally occurring geological conduits are filled with native fluids and are frequently sealed from USDWs by secondary mineralization. This paper concerns itself with only those conduits that are man-made.

Man-made conduits such as old abandoned test holes or oil and gas wells are sealed with cement plugs and drilling mud. The static mud column provides substantial resistance to upward flow. Most mud systems develop a gel structure when allowed to remain quiescent. To initiate flow up an improperly abandoned well bore, the pressure in the disposal zone must exceed the sum of the static mud column pressure and the mud gel strength pressure. If the sum of these values is not exceeded during the life of a hazardous waste disposal well, there is no potential for contamination of USDWs. This paper presents a simplified procedure which can be used to calculate that effected area.

Introduction

The area of review, for a deep injection well, is determined by the zone of endangering influence for the life expectancy of that well. The zone of endangering influence is defined as that area the radius of which is the lateral distance in which pressures in the injection zone may cause the migration of the injection and/or formation fluid into an underg source of drinking water (USDW).

Factors affecting this area of review are the radial extent of ground water movement from the well bore, the rate of pressure build-up in the reservoir, through time, at various distances from the well bore and the potential for upward migration of fluids through man-made conduits.

The prediction of the probable rate of pressure increase and radial fluid movement in the disposal reservoir, resulting from the injection of fluids is a problem often confronted by injection well operators and regulatory agencies. Fluid injected into a formation which is already liquid filled will result in an increase in pressure in that formation. This injected fluid must be accommodated by either one or a combination of the following; expansion of the pore space in the matrix rock, compression of either or both the formation and injected fluids or expulsion of the formation water.

The resulting increase in pressure in the receiving formation due to the injection of fluids pose potential environmental threats to our USDWs if any man-made conduits exist within the area of review. Among the potential conduits for fluid migration from the disposal formation are improperly plugged well bores, channeling behind the casing of the injection well, faulted formations, solution channels, naturally fractured formations or facies pinch-outs.

Factors Effecting the Area of Review

Area of Review

The radius of the area of review for an injection well is determined either by calculating the zone of endangering influence or by using a fixed radius from the well bore which ever is less. The distance of the fixed radius varies from state to state. In states where the Environmental Protection Agency (EPA) has primacy, the fixed radius is 1/4 mile, while in primacy states or states that set their own regulatory standards so long as they meet or exceed EPA standards, the fixed radius varies from 1/4 mile to 2-1/2 miles.

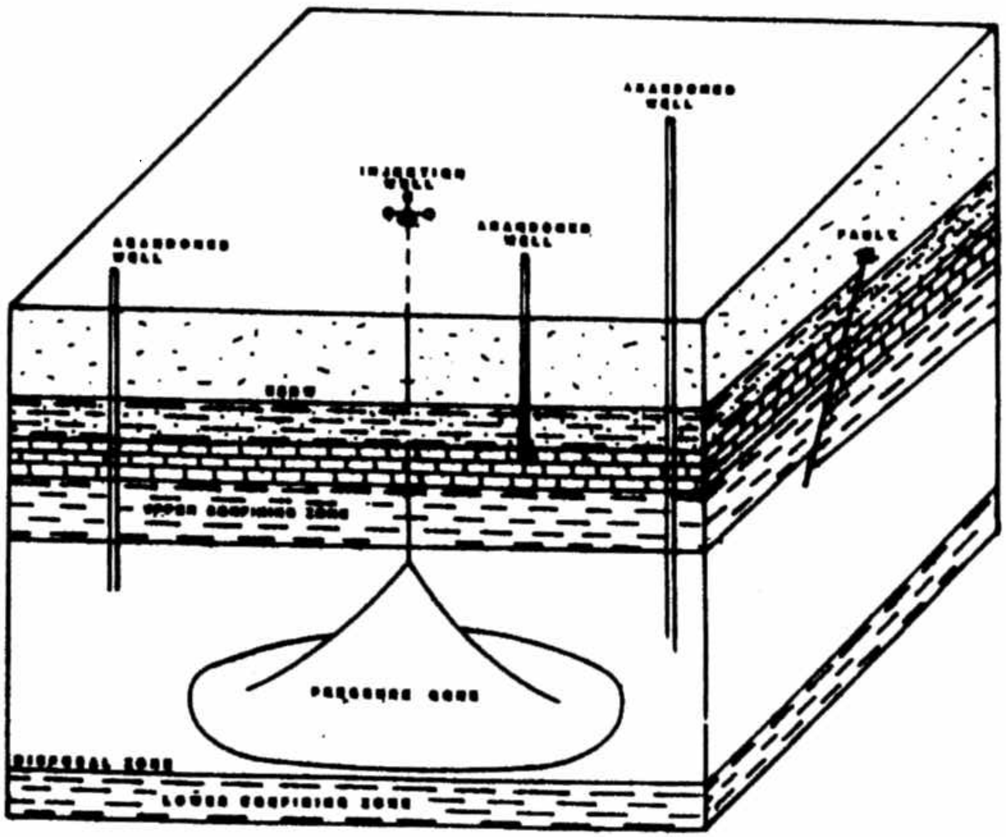
Computation of the zone of endangering influence should be calculated for an injection period equal to the expected life of the well. There are several equations that can be used for determining the area of review. The most notable and widely used is shown below (Barker, 1971; Ferris, et al, 1962; Kruseman and DeRidder, 1970; Lohman, 1972).

$$h = \frac{Q}{4\pi T}\left(-0.577216 - \log_e u + u - \cdots - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} - \cdots\right) \tag{1}$$

where

$$h = \frac{r^2 S}{4Tt}$$

FIGURE 1
SCHEMATIC SHOWING FACTORS
AFFECTING THE AREA OF REVIEW



and

h = hydraulic head change at radius r and time t
Q = injection rate
T = transmissivity
S = storage coefficient
t = time since injection began
r = radial distance from well bore to point of interest.

For large values of time, small values of radius of investigation, or both, Equation 1 can be reduced to:

$$\Delta h = \frac{2.30Q}{4\pi T} \log \frac{2.25Tt}{r^2 S} \tag{2}$$

Unfortunately, this equation does not address all the possible well configurations, multiple well systems, reservoir conditions, skin effects and other variables and combinations thereof. Warner, et al (1979) posed the use of several equations based on specific conditions of the system being evaluated. They indicated that an adequate approximation of the pressure build-up caused by injection into infinite confined reservoirs can be determined if we assume

1. Flow is horizontal.
2. Gravity effects are negligible.
3. The reservoir is homogeneous and isotropic.
4. The injected and reservoir fluids have a small and constant compressibility.
5. The receiving reservoir is infinite in areal extent and is completely confined above and below by impermeable beds.
6. Prior to injection the piezometric surface in the vicinity of the well is horizontal, or nearly so.
7. The volume of fluid in the well is small enough so that the effect of the wellbore can be neglected.
8. The injected fluid is taken into storage instantaneously. That is, pressure effects are transmitted instantaneously through the aquifer.

The basic differential equation for the unsteady radial flow of a slightly compressible fluid from an injection or other type well is (Matthews and Russell, 1967)

$$\frac{\partial^2 P}{\partial r^2} + \frac{1}{r}\frac{\partial P}{\partial r} = \frac{\phi u c}{k}\frac{\partial P}{\partial t} \tag{3}$$

where:

Symbol	Parameter or Variable	Practical Units
c	compressibility	psi^{-1}
Q	porosity	decimal fraction
h	reservoir thickness	feet (ft)
k	permeability	millidarcies (m)
u	viscosity	centipoise (cp)

p	pressure	psi
q	flow rate	stock tank barrels/day (STB/I
r	radial distance	feet (ft)
t	time	days (D)

The pressure build-up equations used by Warner, et al (1979) wer written using dimensionless pressure (P_D) and dimensionless time (t_D). These dimensionless quantities are groups of variables that commonly occu in build-up equations and can be conveniently replaced by a single term Dimensionless time, for the units listed above is:

$$t_D = \frac{6.33 \times 10^{-3} kt}{\phi \mu c r^2} \quad (4)$$

In unsteady state or transient flow equations, dimensionles pressure (P_D) is a function of dimensionless time and, perhaps, othe quantities, depending on the particular buildup solution. It is define for each equation in which it is used, throughout the Warner report.

The Warner equations presented all contain the variable β, th formation volume factor, which is the ratio of the volume of the flui being injected at reservoir pressure compared with the volume a standard conditions (520°R, 14.7 psi). For liquids, β can, fo practical purposes, be considered to be 1.0, as in all examples in thi report. However, β is quite variable when the injected fluid is gas When a highly compressible fluid is being injected, β should b evaluated at an average reservoir pressure. In cases where the pr ur is not known, enter a value of β = 1.0, obtain the approximate pre then evaluate β (Amyx, et al, 1960) and recalculate the pressure.

Multiple Well Effects

As indicated in Figure 2, if we assume a constant injection rate fo a single well penetrating the entire receiving aquifer, and adjust fo practical units, the differential equation, Equation 3, has a solution o the form

$$P_r = P_i + 70.6 \frac{q\mu\beta}{kh} [Ei \left(\frac{39.5 \phi\mu c r^2}{kt}\right)] \quad (5)$$

and for the case where $1/t_d < 0.01$. This is approximated as

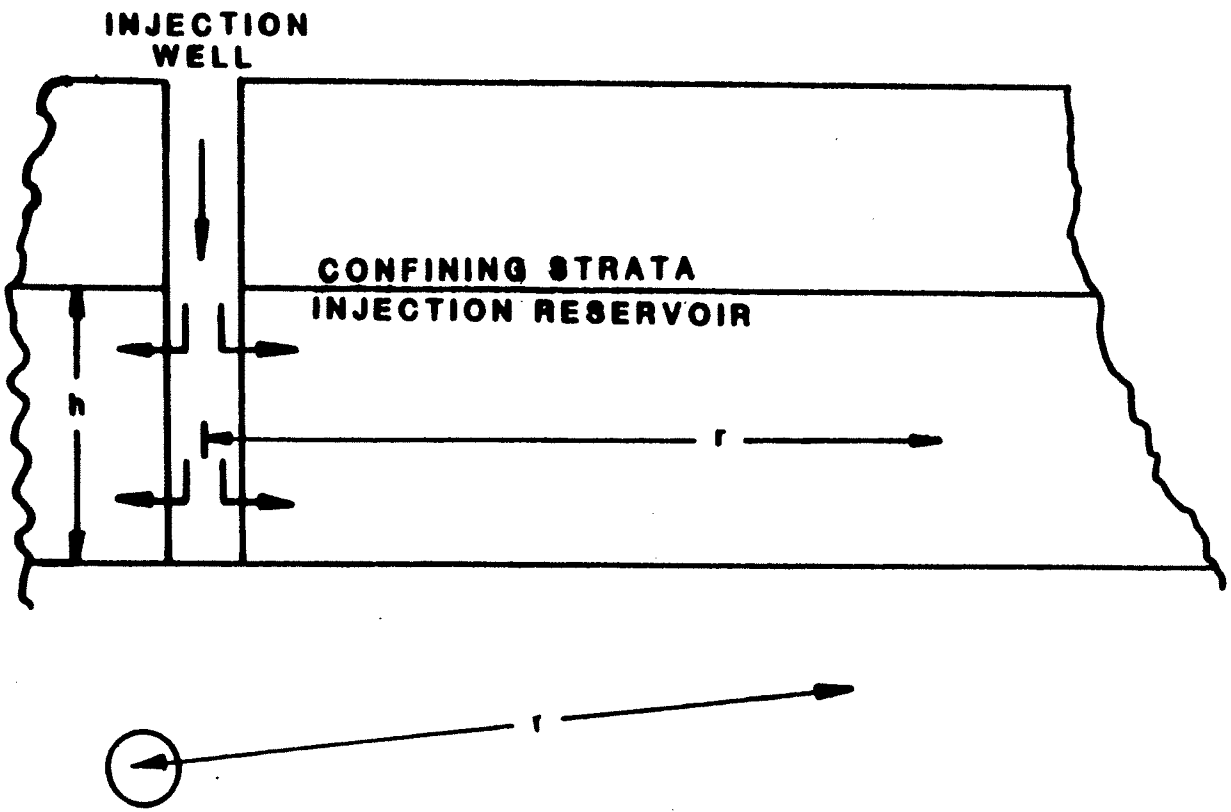
$$P_r = P_i + 162.6 \frac{q\mu\beta}{kh} \log\left(\frac{kt}{70.4 \phi\mu c r^2}\right) \quad (6)$$

where

FIGURE 2

PROFILE AND PLAN VIEWS OF A COMPLETELY PENETRATING WELL INJECTING INTO A CONFINED RESERVOIR. PRESSURE IS TO BE CALCULATED AT A POINT r DISTANCE FROM THE WELL.

(FROM WARNER, et.al. 1979)



Symbol	Parameter of Variable	Practical Units
β	formation volume factor	Std Stk Tank BBL (RB/STB)
P_r	reservoir pressure at radius r	psi
P_i	initial reservoir pressure	psi

A convenient characteristic of these equations (Warner, 1979) is that the effects of individual wells can be superimposed to obtain the combined effect of multiple wells. As indicated in Figure 3, the pressure at any given point in a reservoir can be evaluated by summing the pressures caused by each of the individual injection wells. Assuming the same criteria as in Equations 4 and 5 above, except for multiple wells, we have

$$P_r = P_i + 70.6 \left[\sum_{n=1}^{m} \frac{q_n \mu_n \beta_n}{k_n h_n} \mathrm{Ei} \left(\frac{39.5\ \phi_n \mu_n c_n r_n^2}{k_n t_n} \right) \right] \tag{7}$$

where n is the well number.

For cases where $1/t_d < 0.01$, an adequate approximation is

$$P_r = P_i + 162.6 \left[\sum_{n=1}^{m} \frac{q_n \mu_n \beta_n}{k_n h_n} \log \left(\frac{k_n t_n}{70.4\ \phi_n \mu_n c_n r_n^2} \right) \right] \tag{8}$$

If we assume a variable injection rate for the same criteria as previously applied, the applicable equation is

$$P_r = P_i + 70.6 \left[\sum_{a=1}^{n} \frac{(q_a - q_{a-1}) \mu \beta}{kh} \mathrm{Ei} \left(\frac{39.5\ \phi \mu c r^2}{k(t - t_{a-1})} \right) \right] \tag{9}$$

For cases where $1/t_d < 0.01$

$$P_r = P_i + 162.6 \left[\sum_{a=1}^{n} \frac{(q_a - q_{a-1}) \mu \beta}{kh} \log \left(\frac{k(t - t_{a-1})}{70.4\ \phi \mu c r^2} \right) \right] \tag{10}$$

where a is the time interval under consideration and q_a is the rate during that time interval.

These equations are based on the principle of superposition. That is, the pressure effects begin with the initial injection period t_1 and rate q_1. When a new rate q_2 is implemented, it is as if a new well begins to operate at that rate, with the effects superimposed on the original well, while the original well continues to operate at rate q_1. This performance is shown diagrammatically in Figure 4.

FIGURE 3

PROFILE AND PLAN VIEWS OF TWO COMPLETELY PENETRATING WELLS INJECTING INTO A CONFINED RESERVOIR. PRESSURE IS TO BE CALCULATED AT A POINT AT RADII r_1 AND r_2 FROM WELLS 1 AND 2 RESPECTIVELY.

(FROM WARNER, et.al. 1979)

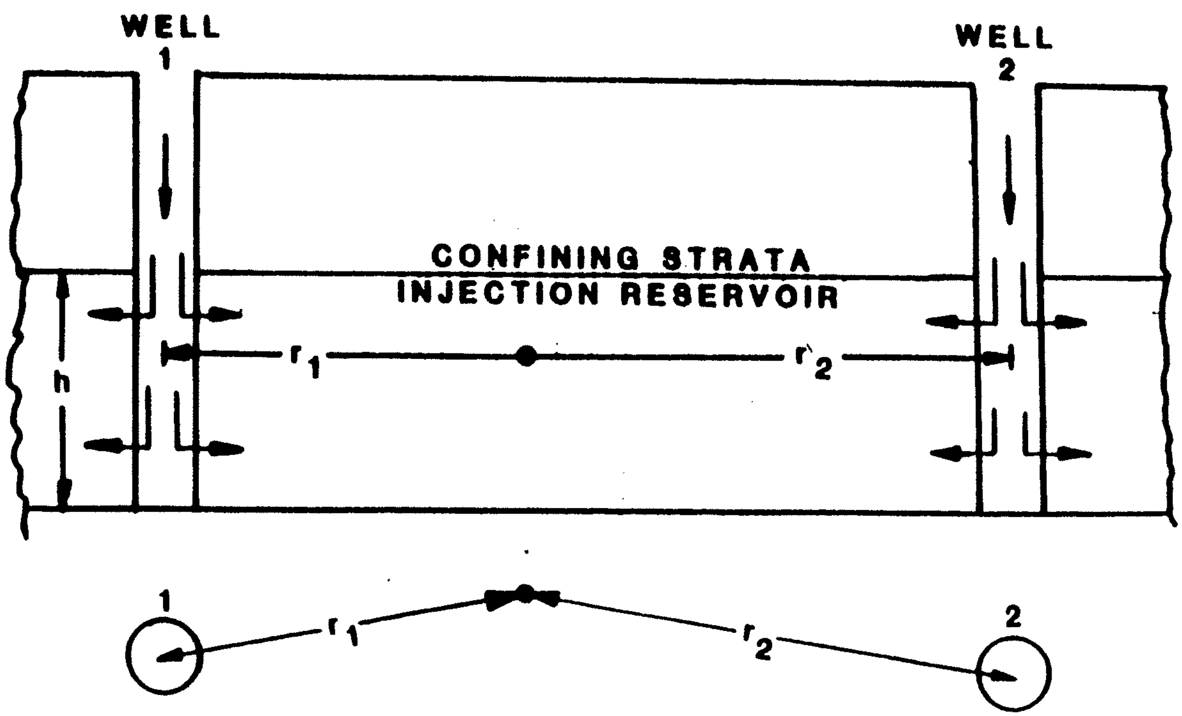
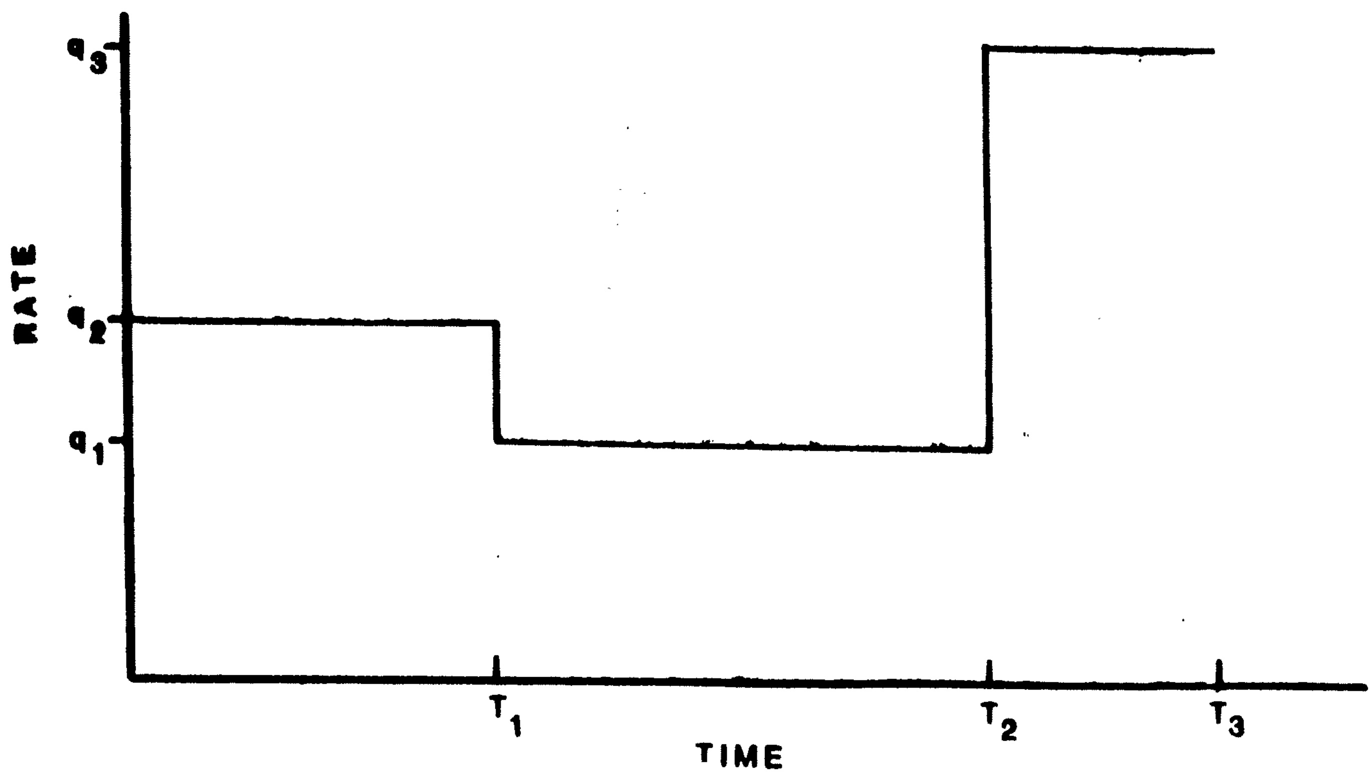


FIGURE 4

DIAGRAMMATIC REPRESENTATION OF THE INJECTION HISTORY OF AN INJECTION WELL OPERATING AT A VARIABLE RATE,

(FROM WARNER, et.al. 1979)



In computing the pressure buildup caused by multiple injection wells operating at variable rates, the principle of superposition is applied twice, once for computation of the pressure effects of each well and a second time in summing the effects of the individual wells. Figure 2 depicts two wells whose effects must be summed and Figure 3 shows a possible pattern of variable rate injection that might exist.

The applicable equation is:

$$P_r = P_i + \left[\sum_{b=1}^{m} \sum_{a=1}^{n} \frac{70.6(q_{ba} - q_{b(a-1)})}{k_b h_b} \, Ei \left(\frac{39.5 \phi_b \mu_b c_b r_b^2}{k_b (t_b - t_{b(a-1)})} \right) \right] \quad (11)$$

Where b is the well number, a is the time interval under consideration for well b, and q_{ba} is the rate for well b during time interval a. For cases where $1/t_d < 0.01$, an adequate approximation is:

$$P_r = P_i + \left[\sum_{b=1}^{m} \sum_{a=1}^{n} \frac{162.6(q_{ba} - q_{b(a-1)})}{k_b h_b} \log \left(\frac{k_b (t_b - t_{b(a-1)})}{70.4 \phi_b \mu_b c_b r_b^2} \right) \right] \quad (12)$$

In summary, these two equations state and perform the calculation for each well, as done for the single-well variable-rate case and then sum the effects of the wells.

Skin Effects

Warner, et. al. (1979) also addressed the effects of skin damage. Injection wells may suffer permeability loss in the vicinity of the wellbore during construction or operation or they may experience permeability gain. Permeability loss can result from drilling mud invasion, clay-mineral reactions, chemical reactions between injected and aquifer water, bacterial growth, etc. Permeability gain can result from chemical treatment such as acidization or from hydraulic fracturing and other mechanical stimulation methods. These permeability changes, which occur in the immediate vicinity of the wellbore are called "skin effects" by the petroleum industry and are described by a "skin factor" (van Everdingen, 1953; Hurst, 1953). The skin factor (s) is positive for permeability loss and negative for permeability gain.

The skin factor can vary from about −5 for a hydraulically fractured well to + ∞ for a well that is completely plugged (Earlougher, 1977). The incremental pressure difference caused by the skin effect is described by:

$$\Delta P_s = s \frac{q}{2\pi kh} \quad (13)$$

Equation 13 is applied by combining it with equations that are derived for pressure buildup without skin effects. For example, Equation 5 is rewritten below to include skin effects:

$$p_r = p_i + \frac{70.6q\mu\beta}{kh} [Ei\left(\frac{39.5\phi\mu cr^2}{kt}\right) + 2s] \quad (14)$$

When $1/t_d < 0.01$, an adequate approximation of Equation 14 is:

$$p_r = p_i + 70.6 \frac{q\mu\beta}{kh} [\ln\left(\frac{kt}{70.4\phi\mu cr^2}\right) + 2s] \quad (15)$$

Equations 14 and 15 are only valid at the wellbore. No equations ar presented here for calculation of pressure buildup near the wellbore, i the zone of damage or improvement, because this zone is relatively thi and because the calculations are of relatively limited applicaton Outside of the skin zone, the standard equations can be applied with n correction (Earlougher, 1977). The thickness of the skin is determined b (Hawkins, 1956):

$$r_s = r_w e^{s\ k_s/k-k_s} \quad (16)$$

Seldom if ever, will k_s be known. Reasonable estimates of k can, however, be made to allow calculation of the range of possible ski thicknesses. Consideration of the sources of permeability reductio around a wellbore indicates that, in the case of wellbore damage, r would seldom be greater than a few feet. The radius of permeabilit improvement can be greater, in the tens of feet for an ordinary hydrauli fracturing program, but probably less than 100 feet as the maximum r_s except in cases of massive hydraulic fracturing.

It should be noted that these equations can only be used for pre buildup at the well. As discussed above, s is assumed to be zero and th ordinary buildup equations should be applied for points outside of th skin zone, which is estimated by Equation 16 or assumed to be less tha 100 feet, if Equation 16 can not be used.

It is generally assumed, in estimating the pressure effects o injection wells, that the wells will be drilled completely through th injection reservoir. This will usually be true, since it maximizes th injection efficiency of the well. However, for mechanical or geologica reasons, drilling is sometimes stopped before complete penetration of th reservoir has been achieved. Such wells are described as partiall penetrating. In other cases, a well may be drilled completely through reservoir, but only a part of the reservoir is completed for injectior Figure 5 depicts partially penetrating and partially completed wells. Th equation for pressure buildup as a result of injection into (pumping from such a well (Hantush, 1964; Witherspoon, et al, 1967) is:

$$p_r = p_i + p_{DPP}\left(\frac{141.2q\mu\beta}{\phi\mu cr^2}\right) \quad (17)$$

where:

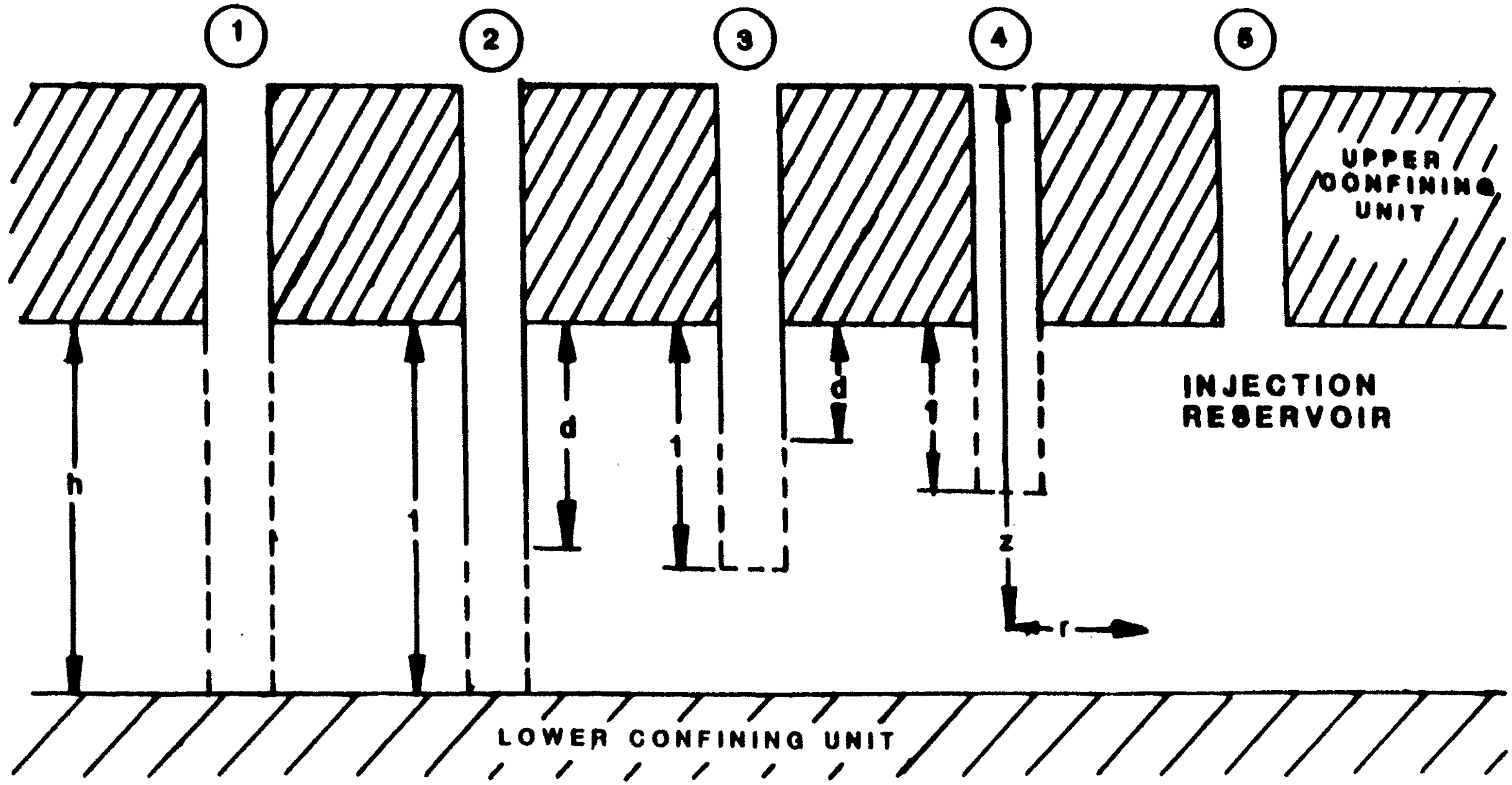
$$p_{DPP} = \frac{1}{2} [Ei \left(\frac{1}{4t_D}\right) + f(r, h, l, d, z)]$$

FIGURE 5

WELLS WITH VARYING DEGREES OF PENETRATION AND COMPLETION

1. FULLY PENETRATING FULLY COMPLETED WELL.
2. FULLY PENETRATING PARTIALLY COMPLETED WELL.
3. PARTIALLY PENETRATING PARTIALLY COMPLETED WELL.
4. PARTIALLY PENETRATING FULLY COMPLETED WELL.
5 NON-PENETRATING WELL.

(FROM WARNER, et.al. 1979)



Partial penetration results in greater pressure buildup (decline) a and near the wellbore than would be experienced in a fully penetr--ir well for the same injection (pumping) rate. The magnitude of diff depends on the degree of penetration, l; the ratio of the radiu investigation to aquifer thickness, r/h; the length of the complete interval, l-d; and the vertical point of investigation, z. The expande form of Equation 17 is too complex for practical use by hand and th number of variables so large that is is impractical to provide tables fo evaluation of P_{DPP}. Computer programs have been developed to solv Equation 17 by Warner, et al (1979).

Warner, et al (1979) also addressed the effects of fracture reservoirs, infinite semiconfined reservoirs, bounded reservoirs reservoirs with variable permeability, reservoirs with radially varyin permeability and fluids of variable viscosity. Although all thes possibilities may effect pressure buildup within a reservoir an therefore, the area of review, their specific values are rarely known Normally these values can only be determined through well testin utilizing pressure buildup and fall off or step rate injection testing Reasonable estimates can normally be made with the aforementione equations and adjusted for these parameters after operating the system fo a reasonable period of time.

Criteria for Eliminating Potential USDW Contamination through Geologica Barriers

Geohydrological Factors

Several geohydrological factors must be considered when studying th area of review for deep well injection. The subsurface environment is complex physical and chemical system. Before the injection of fluids int this system can be permitted, it must be evaluated for its ability t contain the wastes. Upward migration of wastes can occur through eithe natural geologic or man-made pathways. Natural geologic conduits such a faults, solution channels or fractures are usually filled with nati fluids and are frequently sealed from USDWs by secondary mineralizatio Man-made conduits such as old abandoned test holes or oil and gas well are sealed with cement plugs and drilling muds. However, the chemica effects of the injected waste on the formation rock and conduits, if any must also be evaluated. When evaluating these phenomena, we must remembe that chemical reactions in the subsurface are normally very slow an equilibrium is reached very quickly. Since fluid movement in th subsurface is very slow, diffusion is the primary mixing factor an provides additional support to waste containment near the well bore. we consider all the rocks that are commonly penetrated when a well drilled, the rock most susceptible to blocking both artificial and natur conduits is shale. Both sandstones and carbonate rocks can becom unstable, and fill a well bore or annular space when subjected to tecton stresses or when the hydrostatic mud pressure is lower than the pressu on the fluids within the rocks, particularly when the permeability is lo The instability of shale, on the other hand, is compounded t extraordinary manner that this rock is affected when exposed to wate

Reaction of Shales and Clays

Shales are essentially rocks that contain clay. Shale rocks are formed by the compaction of sediments. Water is squeezed out as sediments are buried deeper by layers deposited progressively during geologic time. The degree of compaction of the sediments is proportional to the depth of burial, provided the water is able to escape easily to permeable strata. The younger sediments soften and disperse when mixed with water. The older shales usually have undergone diagenesis, may remain hard and are less easily dispersed into water. The term shale is applied to everything from clays to lithified materials such as slate. Soft clays are extremely reactive with water while slates are relatively inert. Because the various shales behave differently upon exposure to drilling fluids when penetrated by the bit, it is useful to classify shales so that instability may be approached in a somewhat systematic manner. Such a classification is shown in Table I.

The amount of clay, the type of clay, the depth of burial, and the amount of water in a given shale all relate to the stability of the shale. The amount of clay in a given shale depends on the composition of the shale sediments at the time of deposition. The type of clay in a given shale depends not only on sediment composition at the time of deposition, but also on changes that may occur in the clay after burial.

From the view point of effect on hole stability, clays may be classified broadly as expandable and non-expandable. Expandable clays exhibit a high degree of swelling when wetted with water. Expandable clays as a group are called smectites. Montmorillonite (bentonite) is a high-swelling member of the smectite group. The non-expandable clay most commonly found in shales is illite. Chlorite and kaolinite are non-expandable clays often found in shales as well. Non-expandable clays swell much less than expandable clayes on being wetted with water. The degree of swelling of both clay types varies greatly with the type and amount of salt dissolved in the water with which the clay is wetted (R.E. Grim, 1968).

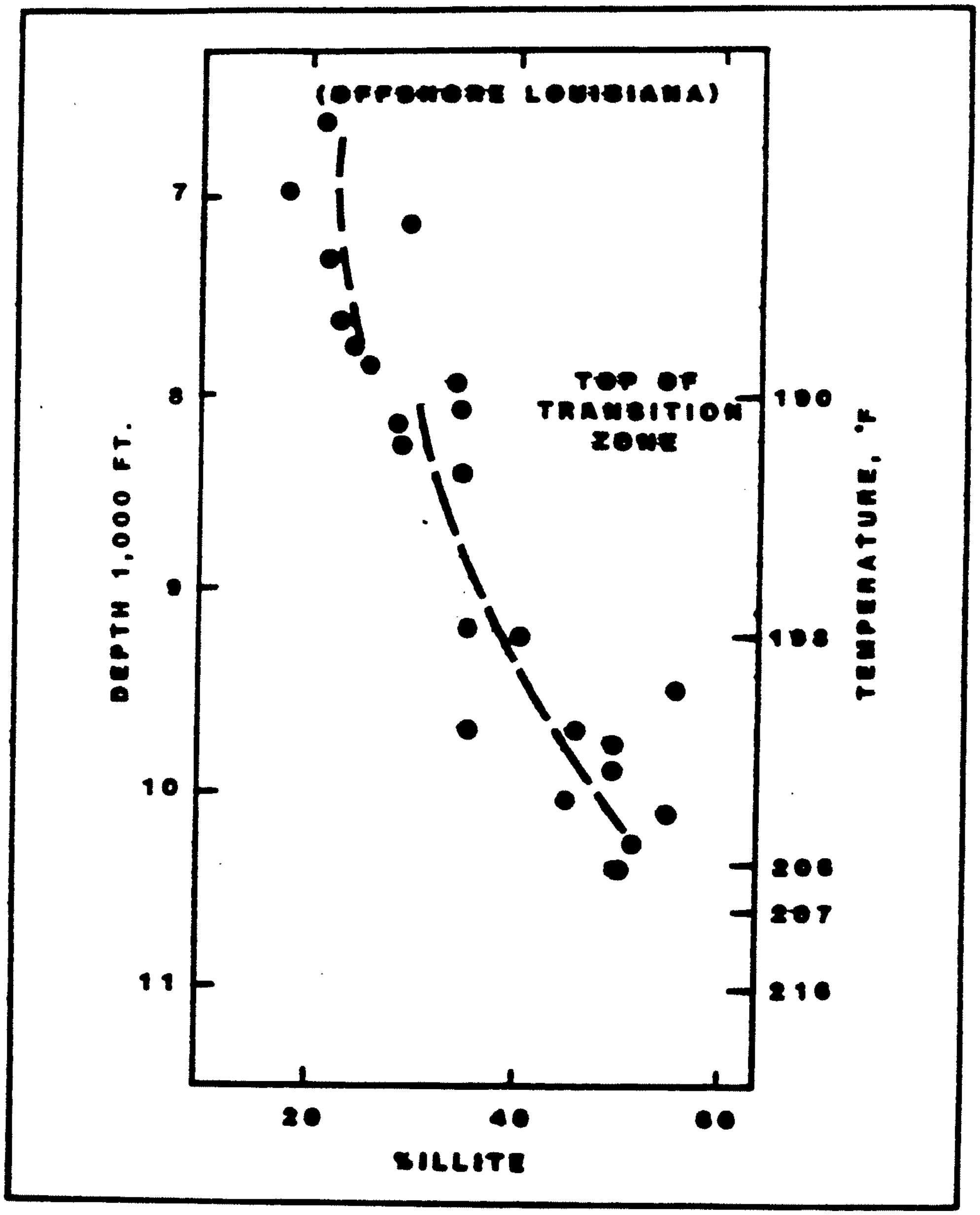
The type of clay in younger sediments depends in large part on the temperature at depth of burial. A change in clay mineralogy with depth is illustrated in Figure 6 (W.H. Fertl and D.J. Timko, 1970). The increasing percentage of illite with depth is attributable to alteration of smectite to illite. The alteration phenomenon is called "diagenesis". Some water of crystallization is released from the expandable clay during diagenesis. Illite differs from montmorillonite structurally in that some of the silicons in the outer silicate layers (R.E Grim, 1968) of illite are always replaced by aluminums, and the resultant charge deficiency is balanced by potassium ions (R.E. Grim, 1968). Temperature, rather than pressure, is thought to be the critical variable in the reaction through which this change is brought about.

The amount of water in a given shale depends on the depth of burial and the type of clay in the shale. Loosely bound water is squeezed out of the shale by pressure exerted by the weight of the overburden of the earth at depth of burial. A good approximation of the magnitide of overburden pressure is 1 psi/ft of depth. A laboratory experiement that illustrates

FIGURE 6

LATTICE MIXING

(FROM FERTLAND AND TIMKO)



this phenomenon is presented graphically in Figure 7 (H.C.H. Darley, 1969). Both bentonites in this illustration are expandable clays, and the Ventura shale contains mostly non-expandable clays. Most of the free water that can be easily squeezed out of the expandable clays is freed with a effective pressure of 2500 to 2000 psi. A matrix (grain to grain) stress of this magnitude would be expected in the crust of the earth at a depth of about 4500 to 5500 feet. Additional water is released as the swelling clays are subjected to even greater effective pressures.

Causes of Shale Instability

Shale instability may result from the following forces, either singly or in combination:

1. Overburden pressure
2. Pore pressure
3. Tectonic forces
4. Water adsorption
    a. Dispersion
    b. Swelling

Various forms of hole instability arise when the stress relief of overburden pressure occasioned by drilling exceeds the yield strength of the formation. A well-known example of this phenomenon is the plastic flow that occurs in geopressured shales. The water content and the plasticity of the shale are abnormally high relative to the overburden load, and the shale is extruded into the hole in plastic flow.

When the pressure of the drilling fluid is less than the pressure of the fluids within the pores of the rock being drilled, the pressure differential toward the hole tends to induce fragments of rock to fall into the hole. Such caving is more likely to occur when the rock is relatively impermeable. The strength of the rock is a factor in this process as well.

Tectonic forces result from stresses imposed on a given stratum by deformation of the crust of the earth. Such deformation is commonly described as folding and faulting, and is a normal result of the formation of mountains. Stresses thus created are relieved quickly in shale that is readily deformable, but tend to remain in rocks that are brittle. Even a small amount of water adsorption can cause sufficient stress to induce shales to flake off in fragments and slough into the hole.

Shale Classifications

Reference to a shale classification like the one given in Table I is helpful for a description of the effect of water absorption on shale stability. Because the number of combinations of physical and chemical properties of rocks called "shale" is so large, a classification of some kind is necessary for a logical and organized approach to predict the probability of occurrence. For purposes of illustration, a description follows of how shales of Class A through E behave upon wetting with fresh water. Obviously the behavior of the different classes of shale would be different in various salt solutions.

FIGURE 7
WATER RETAINED UDER LOAD
(FROM DARLEY)

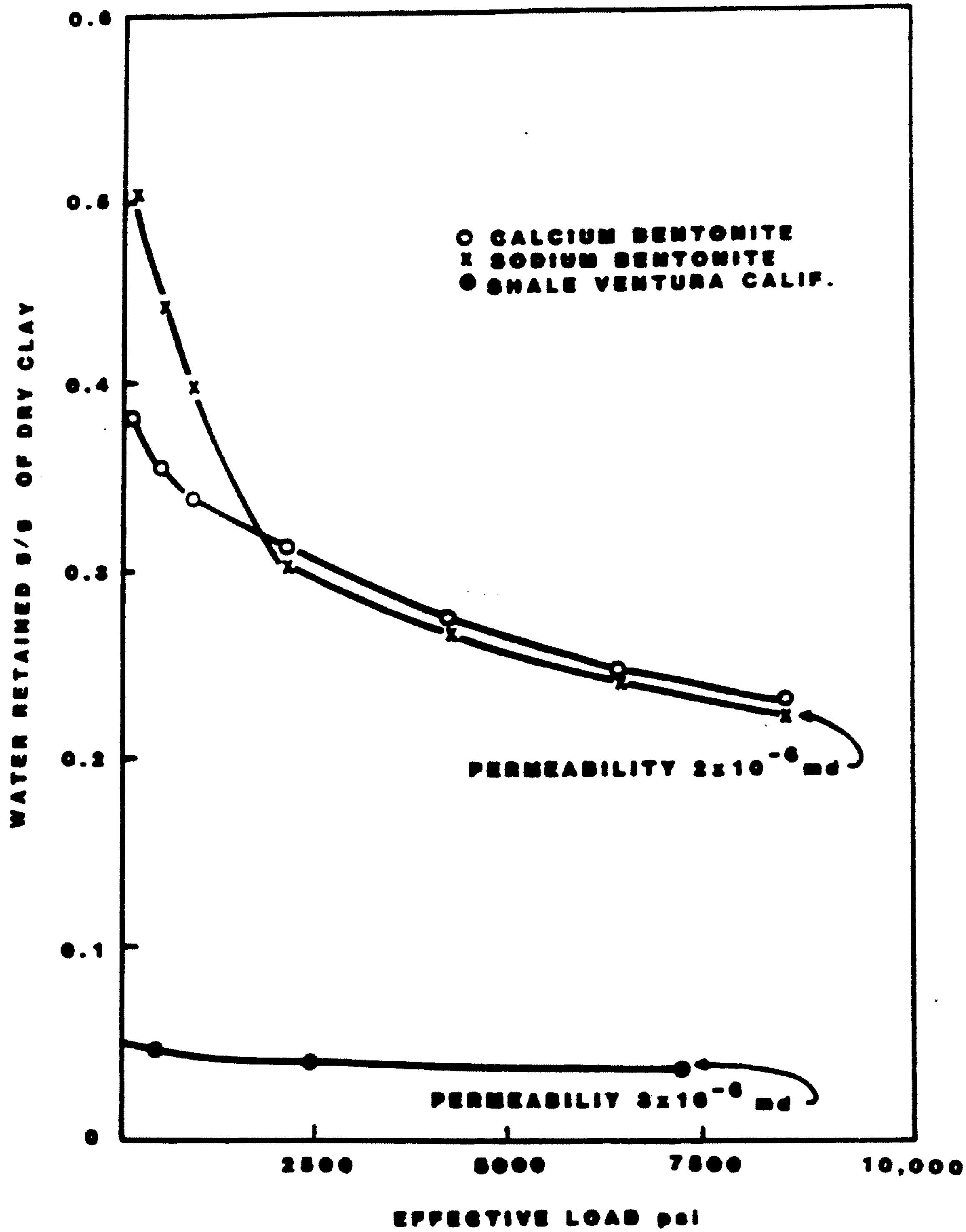


TABLE 1

A GENERAL SHALE CLASSIFICATION

Class	Texture	Methylene blue capacity (me/100g)	Water Content	Wt% Water	Clay Content	Wt% Clay	Density g/cc
A	Soft	20-40	Free and bound	25-70	Montmorillonite and illite	20-30	1.2-1.5
B	Firm	10-20	Bound	15-25	Illite and mixed layer montmorillonite-illite	20-30	1.5-2.2
C	Hard	3-10	Bound	5-15	Trace of montmorillonite high in illite	20-30	2.2-2.5
D	Brittle	0-3	Bound	2-5	Illite, kaolin chlorite	5-30	2.5-2.7
E	Firm-hard	10-20	Bound	2-10	Illite and mixed layer montmorillonite-illite	20-30	2.3-2.7

(From Mondshine 1969)

Class-A shale is characterized primarily by high-water content an relatively high expandable clay content. The word montmorillonite as use in Table I denotes expandable clays as identified by the methylene test. The word smectite is now a more widely accepted group Montmorillonite is a member of the smectite group. Shale of this qua..t is often found at shallow depth where the overburden load is still to small to have squeezed more water from the sediments during compaction and the temperature too low to have induced diagenesis. The same shal may also be found at greater depth when permeable avenues for the escap of connate water did not exist, and where conditions were not right fo montmorillonite to have been altered to illite (see Figure 6). When stil more water is added to Class A shale, it would be expected that th compaction process would be to a degree reversed. In the higher wate content range, this shale could also be squeezed into the hole from th pressure created by the weight of the overburden. The lower the mu weight, the more likely it would be for this phenomenon to occur.

Class-B shale would respond to adsorption of fresh water mainly b becoming more plastic or less firm. Water would penetrate slowly from th borehole into the shale body. Capillary adsorption of water into beddin planes would occur nominally if at all, because of the smectite clays i the shale. Abnormal pore pressure in shale of this description i possible. Aside from possible pressure effects, Class-B shale woul usually remain rather stable after being penetrated.

Class-C shale would be more likely to slough into the hole tha either Class A or B. This type of shale would be found in sediment similar to those that constituted Class-B shale, but at greater d h Some softening would occur upon adsorption of fresh water. Very l there would be sections where the shale would still be hard after wate adsorption and some swelling, so that some fragments would disengage fro the matrix and fall into the hole. The mechanism of fragmentation coul be the result of either capillary adsorption along bedding planes, o simply penetration of water into the shale body away from the hole.

Class D shale may be found at both shallow and great depths, but i likely to be quite old geologically. Brittle shale subdivides into smal particles when immersed in water, but swells and softens very little if a all. It is believed that cleavage takes place along old fracture plane that are held together by attractive forces that act over short distance only. Hydration when contacted by an aqueous drilling fluid cause separation at the old fracture planes.

Class E shales are likely to be found quite deep, and are usuall abnormally pressured. Occurrence of this type of shale is sometime thought to be anomalous, even though it is found quite often in sediment of tertiary age. This shale would have a strong tendency to slough upo adsorption of fresh water. In interbedded smectite-illite intervals illite ledges may be borken off by the unequal degree of swelling of th two different shales.

Shale Hydration

Water wetting of shale can and usually does result in borehole blockage. The instability usually results primarily from overburden pressure, pore pressure, or tectonic stress. This is true regardless or whether the clay in the shale is largely expandable or non-expandable, or whether the shale in place is brittle or plastic. Moreover, shale disperson, hole closure or sloughing from shale swelling are all attributable to adsorption of water by shale.

The forces that cause shale to absorb water are attributable to the clay in the shale. It should also be emphasized at the outset that these forces through which clay adsorbs, imbibes, draws or sucks water into itself can be very great. By comparison the force with which mud filtrate may be pressed into the formation by the differential between the hydrostatic pressure of the mud column and the pore pressure of the formation is very small. For example, if a normally pressured stratum at 5000 or 10,000 feet on the Gulf Coast is drilled with 9.5 ppg mud, the pressure differential would be about 125 and 250 psi respectively. This figure represents the pressure with which filtrate from the mud is being pressed into the formatio by the overbalance of hydrostatic pressure over pore pressure. The text following will illustrate that the water adsorption forces of shale are much greater.

Hydration of shale depends upon a number of factors such as the hydration energy of the interlayer cations on the clays present and the charge density on the surface of the clay crystals. A reasonable estimate of the shale hydration force can be made by considering the compaction forces involved in subsurface burial of a given shale stratum during geologic time. For well drilling purposes, the hydration force is calculated conveniently in this way. The effective compaction stress on a shale section at any given depth can be represented by the equation, $s = S - P$, where s is the intergranular or matrix stress (W.R. Mathews and J. Kelly, 1967), S is the overburden pressure (approximately 1 psi/ft), and P is the pressure on the fluid in the pores of the rock.

As a given layer of shale is buried deeper, progressively more water is squeezed out of the shale by the weight of the overburden. The force with which water is being expelled from the shale in the compaction process equals the intergranular or matrix stress. The adsorption (or suction) force of the clay acts in opposition to the water expulsion force of compaction. This compacting force is relieved on the borehole face when the shale is penetrated by the bit. Consequently, a hydration force equal to the degree of relief develops. Since the compaction force equals the matrix stress, then:

$$\text{SHALE HYDRATION FORCE}_{psi} = \text{OVERBURDEN}_{psi} - \text{PORE PRESSURE}_{psi}$$

For example, assuming again a normally pressured shale (9 lb/gal mud weight equivalent) at 10,000 ft on the Gulf Coast:

$OVERBURDEN_{psi}$ = 1 psi/ft = 10,000 psi

$MATRIX\ STRESS_{psi}$ = $OVERBURDEN_{psi}$ - $PORE\ PRESSURE_{psi}$

= 10,000 psi - (9 x 0.052 x 10,000) psi

= 5320 psi

The shale hydration force at 10,000 feet in normal pore pressure is therefore 5320 psi.

Drilling Fluids

Artificial penetrations in the area of review or zone of endangering influence can provide potential conduits to USDWs if improperly plugged when abandoned, improperly cemented when constructed or a combination thereof. Artificial penetrations are usually man-made holes used for the exploration of oil and gas or other minerals and water. These holes are rarely empty and are fluid filled with native water, brine or drilling fluid. In the case of native waters or brine the fluids may have seeped into the well bore or been left there by the original driller. If the well was originally drilled with a cable tool rig or rotary drilling rig using compressed air, the fluid in the hole is probably native water or brine. However, the vast majority of artificial penetrations are made exploring for oil and gas. Therefore, it is logical to conclude that most well bores are mud filled since rotary drilling techniques using drilling fluid are predominately used when drilling oil and gas exploration and development wells. Upon completion of the drilling operation, if the well is not completed for production, the drill pipe is removed from the bore and the drilling mud used to drill the well will remain in the bore indefinitely. If the well is completed or casing is run and partially cemented across a portion of the well bore, drilling mud would have been displaced ahead of the cement from the annular space between the casing and open hole. If cement was not circulated to the surface, then the annular space above the cemented section will be filled with drilling mud.

A fluid filled well bore or annular space provides resistance to upwards fluid migration because of two opposing forces. The first would be the hydrostatic head or downward force caused by the weight of the fluid column. This can be described as psi/foot of depth by taking the weight of one cubic foot of water and dividing it into 144 square inches one-foot high. A cubic foot of water weighs approximately 62.3 pounds dividing by 144 square inches, we find that a column of water one-foot high exerts a downward pressure of 0.433 psi. Therefore a column of water 1000 feet deep would provide a downward force of 433 psi. If fluid were migrating upward, it would have to have a driving force in excess of 433 psi. This example used fresh water having a density of 8.33 lbs/gal. The second opposing force that would act as a deterent to fluid migration along a well bore would be present only if the fluid filling the well bore had gel strength. Most drilling fluids contain this characteristic.

One of the primary functions of the drilling mud is the removal of drilled cuttings from the well bore. The mud carries the cuttings from beneath the bit, transports them up the well bore/drill pipe annulus and releases them at the surface. Since normal drilling operations require that mud circulation be stopped periodically to add another joint of drill pipe, the mud must have a property which acts to suspend the drilled cuttings in the static mud column. This property is known as gel strength. Gel strength is time dependent and increases as the mud column remains quiescent. Most drilling fluids are thixotropic and develop a gel structure like "Jello" when allowed to stand quiescent but become fluid when disturbed.

To determine the combined effect of both hydrostatic head and gel strength acting as a deterrent to fluid migration along a mud filled well bore or annulus, we must first identify the forces acting on a well bore and/or annulus existing in a static state. Figure 8 represents a vertical force diagram of a static mud column in an abandoned well that contains no uncemented casing. Figure 9 represents the forces acting on the static mud column in the annulus between the casing and open hole above the cemented interval.

The equation for the force balance in Figure 8 takes the following form,

$$w + GS_w(2\pi r_w h) = P_f(\pi r^2_w) - P_t(\pi r^2_w) \qquad (18)$$

where

$$w = r^2_w \rho h$$

and

w = weight of mud column
GS_w = gel strength of mud column acting on circumference area of well bore
P_t = pressure at top of well
P_f = pressure at formation being contained
r_w = radius of well bore
h = height of mud column in well bore
ρ = density of mud

Simplifying the force balance and adjusting for standard units, we obtain the following pressure equation,

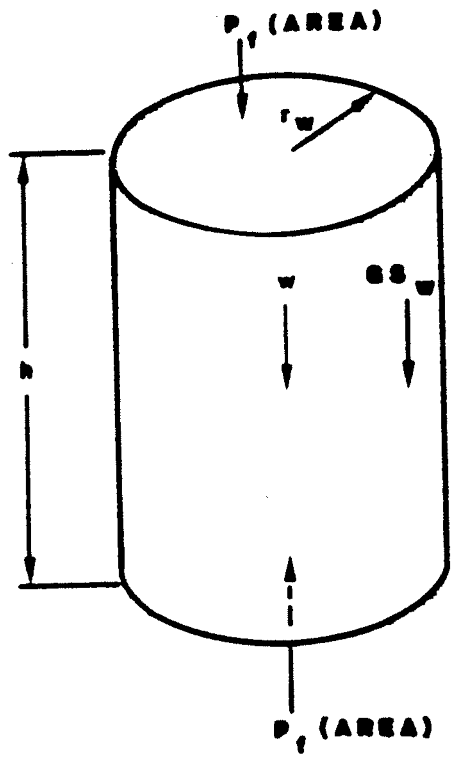
$$P_f = P_t + 0.052\rho h + 3.33 \times 10^{-3} GSh/D \qquad (19)$$

where:

P_f = pressure at the contained formation in psi
P_t = pressure at the top of well
ρ = density of mud in lb/gal
h = height of mud column in feet
GS = gel strength in lb/100 ft^2
D = diameter of well bore in inches

FIGURE 8

STATIC MUD COLUMN
FORCE BALANCE DIAGRAM



P_t (AREA) = PRESSURE AT THE TOP OF WELL $= P_t \pi r_w^2$

W = WEIGHT OF FLUID COLUMN $\rho h \pi r_w^2$

GS_w = GEL STRENGTH OF MUD A ON CIRCUMFERENCE AREA OF WELL BORE $= GS_w (2 \pi r_w h)$

P_f (AREA) PRESSURE AT THE FORMATION BEING CONTAINED $P_f \pi r_w^2$

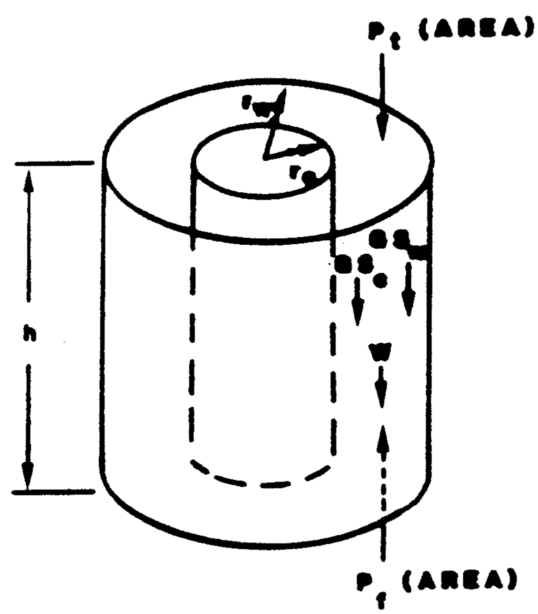
FORCES FROM MUD COLUMN SUM OF PRESSURE FORCES

$$w + GS_w (2\pi r_w h) = P_f (\pi r_w^2) - P_t (\pi r_w^2)$$

FIGURE 9

ANNULUS STATIC MUD COLUMN
FORCE BALANCE DIAGRAM

WELLBORE ANNULAR EFFECTS



FORCES FROM MUD COLUMN = SUM OF PRESSURE FORCE

$$W+GS_c(2\pi r_c h)+GS_w(2\pi r_w h) = P_f \pi(r_w^2-r_c^2)-P_t \pi(r_w^2-r_c^2)$$

The force balance equation for Figure 2 takes the form

$$w + GS_c(2\pi r_c h) + GS_w(2\pi r_w h) = P_f\pi(r^2_w - r^2_c) - P_t\pi(r^2_w - r^2_c) \quad (20)$$

where

$$w = \rho h(r^2_w - r^2_c)$$

and

- w = weight of mud column in annulus
- GS = gel strength of mud acting on circumference area of both the well bore (GS_w) and casing wall (GS_c) and $GS_w = GS_c$
- P_t = pressure at top of well
- P_f = pressure at formation being contained
- r_w = radius of well bore
- r_c = outside radius of casing
- h = height of mud column in annulus
- ρ = density of mud

Simplifying the force balance and adjusting for standard units, we obtain the following pressure equation,

$$P_f = P_t + .[illegible]\rho h + \frac{3.33 \times 10_{-3} GSh}{D_w - D_c} \quad (21)$$

where:

- P_f = pressure at the contained formation in psi
- P_t = pressure at the top of the well
- ρ = density of mud in lb/gal
- h = height mud column in feet
- GS = gel strength of mud in lb/100 ft^2
- D_w = diameter of well bore in inches
- D_c = outside diameter of casing in inches

Drilling Fluid Properties

It is generally recommended that the values required to calculate th flow resistance of a mud filled well bore or annular space be obtaine from the well records. The physical configuration of the well can usuall be obtained from many sources. These include but are not limited to stat and federal permit records, the owner/operator files, commercia libraries, geological surveys and other public information sources. Th density of the drilling fluid used to drill the well is normally recorde on the geophysical log heading as shown in Exhibit 1. The gel strengt values may be more difficult to obtain. Mud properties are generally ru while conditioning the mud to run casing and cement. These values ar normally determined by the drilling fluid supplier or service company an are reported on standardized forms such as the one shown in Exhibit 2 These data are normally available from the owner/operator's well fi o the service company. Also, it is frequently not necessary to fin

EXHIBIT 1

Schlumberger

BOREHOLE GEOMETRY LOG

COUNTY
FIELD or LOCATION
WELL
COMPANY

COMPANY ____________________

WELL ____________________

FIELD ____________________

COUNTY ____________ STATE ____________

LOCATION

Sec. ______ Twp. ______ Rge. ______

Other Services:

Permanent Datum: ______ , Elev. ______
Log Measured From ______ , ______ Ft. Above Perm. Datum
Drilling Measured From ______

Elev.: K.B. ______
D.F. ______
G.L. ______

Date				
Run No.				
Depth — Driller				
Depth — Logger				
Btm. Log Interval				
Top Log Interval				
Casing — Driller	@	@	@	@
Casing — Logger				
Bit Size				
Type Fluid in Hole				
Fluid Level				
Dens. Visc.				
pH Fluid Loss	ml	ml	ml	ml
Source of Sample				
R_m @ Meas. Temp.	@ °F	@ °F	@ °F	@ °F
R_{mf} @ Meas. Temp.	@ °F	@ °F	@ °F	@ °F
R_{mc} @ Meas. Temp.	@ °F	@ °F	@ °F	@ °F
Source: R_{mf} R_{mc}				
R_m @ BHT	@ °F	@ °F	@ °F	@ °F
Time Since Circ.				
Max. Rec. Temp.	°F	°F	°F	°F
Equip. Location				
Recorded By				
Witnessed By				

EXHIBIT 2

Magcobar

1 | 7205 | 83?E

Salt Gel - Brine

7/29/80

Lea

New Mexico

8 5/8	1204	12¼	1
7	3750	8 3/4	2

Date	Depth	Weight	Vis	[illegible]	P_f	M_f	Chlorides	[illegible]	[illegible]	Daily Cost	Total Mud Cost
1980											
3/1 DRILLING	1050	8.8	30	9			2000	Good	8	314.96	314.96
3/3 DRILLING	1877	10.[illegible]	30	8.5	.1	.8	50,000	Good	9	243.81	558.77
3/4 DRILLING	2206	10.[illegible]	30	9	.2	1	60,000	Good	[illegible]	-0-	558.77
3/5 DRILLING	3202	10.3	30	9	.2	1	100,000	Good	[illegible]	-0-	558.77
3/6 DRILLING	3543	10.[illegible]	30	9	.2	1	100,000	Good	[illegible]	304.30	862.07
3/7 LOGGING	3750	10.2	30	9	.2	.8	60,000	Good	[illegible]	1737.27	2600.1[illegible]

TOTAL [illegible] COST 3245.5[illegible] well records of each well since wells drilled adjacent to each other frequently use the same or similar mud systems. Historical records are also a good source of obtaining conservative values for gel strengths of specific types of drilling fluid systems.

Since the gel strength of different types of mud systems varies, it is difficult to determine the exact gel strength of the mud in a particular well bore. A review of the gel strength characteristics of various types of muds was made to evaluate the factors that effect the gel strength structure. The aim of this review was to provide sufficient information to determine the minimum gel strength structure that could be anticipated for any combination of formation, well bore and mud type. This value can then be used if insufficient data is available for a specific well bore.

Thixotropy is the property, exhibited by certain gels, of liquifying when stirred or shaken and then returning to their gelled state when allowed to stand quiescent. This property in drilling fluids is the result of various clay minerals being used as additives in drilling fluids. Generally, clay particles fall into the colloidal particle range. Colloidal systems used in drilling fluids include solids dispersed in liquids and liquid droplets dispersed in other liquids. These highly active colloidal particles comprise a small percentage of the total solids in drilling muds but act to form the dispersed gel forming phase of the mud that provides the desired viscosity, thixotropy and wall cake properties.

Clay particles and organic colloids comprise the two classes of colloids used when mixing drilling fluids. The common organic colloids include starch, carboxycelluloses and polyacrylomine derivatives.

Barker (1981) reported that, "The clay colloids utilized in common drilling fluids are characterized by a crystalline structure which influences the ability of the clay to retain water." Clays used in fresh water muds consist of hydrated alumnosilicates comprised of alternate plates of silica and aluminum to form layers of each mineral. The plate-like crystals have two distinct surfaces: a flat face surface and an edge surface. Slight surface polarities induce weak electrostatic forces along the faces and edges of the mineral plates. Garison (1939) noted that these electrostatic forces attract planer water to the colloidal particles forcing the clays to swell when wet and shrink when dry. The attraction of planer water to the faces of the plates is greater than the attraction of the sheets for each other therefore the structure tends to swell due to the absorbsion of the planer water from the drilling fluid. The bentonite clays demonstrate a strong ability to attract planer water as a result they experience extreme swelling. When in contact with fresh water, the face to face attraction of water by the mineral layers will continue until the swelling reduces the attraction of the plates to the point where they separate. This separation results in a higher number of particles and is referred to as dispersion. The dispersion causes the colloidal suspension to thicken. The degree of thickening depends on the electrolytic content, salt concentration of the water, time, temperature, pressure, pH, the exchangeable cations on the clay, and the clay concentration.

Gel Strength, The Measure of Thixotropy

Thixotropy is essentially a surface phenomenon which is characte by gel strength measurements. The gel strength indicates the attr forces between particles under static conditions. The strength of th structure which forms under static conditions is a function of the amou and type of clays in suspension, time, temperature, pressure, Ph, and th chemical treating agents used in the mud. Those factors which promot the edge-to-edge and face-to-edge association of the clay particl defined as flocculation increase the gelling tendency of the mud and tho factors which prevent the association decrease the gelling tendency.

Due to their size, colloidal particles remain indefinitely suspension. When suspended in pure water the clay particles will n flocculate. When flocculation occurs the particles form clumps or floc These loosely associated flocs contain large volumes of water. If t clay concentration in the mud is sufficiently high, flocculation wi cause formation of a continuous gel structure instead of individu flocs.

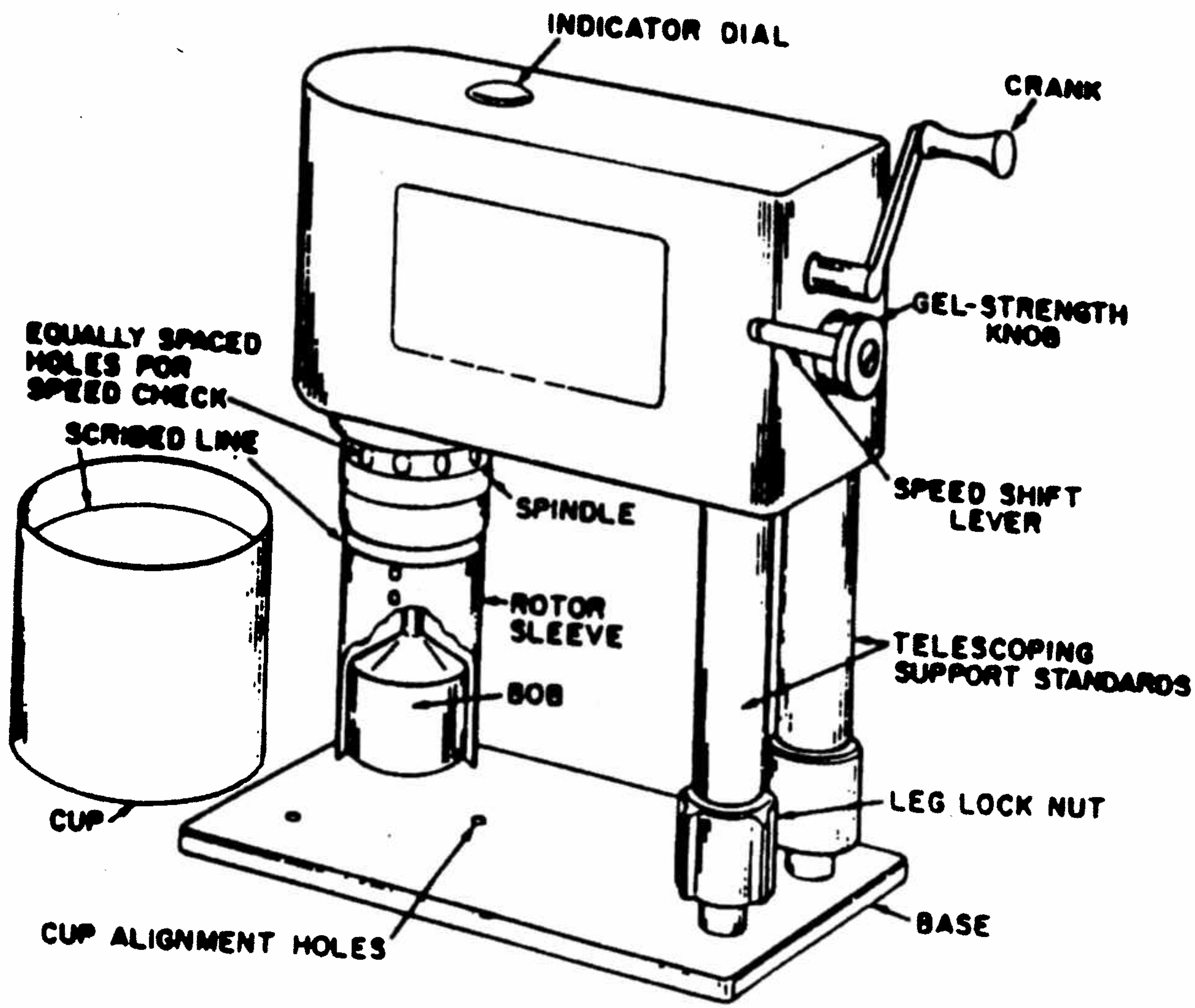
The gel structure commonly observed in aqueous drilling flui results from salt contamination. Soluable salts are usually present sufficient quantities to cause at least a mild flocculation. The ti required for the gel to attain an ultimate strength depends on t critical concentration of electrolyte required to initiate flocculatio the thinners present, and the concentration of the clay and of the sa present. During drilling the presence of salts and clay particles vari with each formation being drilled, therefore the drilling fl monitored and adjustments are made in order to maintain the desi strength.

Gel Strength of the Static Mud Column

Gel strength is measured by a multispeed direct indicating viscome (See Exhibit 3) by slowly turning the driving shaft by hand and observ the maximum deflections before the gel structure breaks. The gel stren is normally measured after quiescent periods of 10 seconds (initial strength) and 10 minutes. The measurements are taken at surf conditions of standard temperature and pressure. To determine the strength of the static mud column in an abandoned well it is necessary determine the gel strength of the mud under the influence of boreh conditions. The initial and 10 minute gel strengths bare to dir relation to the ultimate gel strength of the mud at borehole conditio To determine the ultimate gel strength of a mud it is necessary to disc the factors which act to influence the initial gel strength at boreh conditions.

Once the drilling operation is completed and the well is aband the mud is subjected to conditions vastly different from those encount at the surface. In the range of formation depths utilized for disposa industrial wastes the temperature would be expected to range from 8 300°F, the pressure from 1500 to 5000 psi and time from days to sev years. Several studies have been conducted to determine the i time, temperature and pressure on the gel strength of muds at

EXHIBIT 3
HAND VISCOMETER



conditions. The information obtained from this research should provid means of determining a reasonable minimum gel strength value for abandoned wells which exist in the range of formations described at

It is observed that common use water base muds develop high strengths after prolonged periods of quiescence. The relationship betw gel strength and time varies widely from mud to mud, depending on composition, degree of flocculation, temperature, pH, solids, pressure. Figure 10 (G.D. Gray, H.C. Darley and W.F. Rogers, 19 indicates the increase in gel strength with time for various mud types reveals that there is no well established means of predicting long t gel strengths with time. It is noted in all cases that the gel stren is observed to increase.

Garrison (1939) studied the gel strength in relation to time and r of reaction for California bentonites. He observed that both the sp and the final strength increased with the bentonite percentages. gelling was found to follow the equation:

$$S = \frac{S'kt}{1+kt} \quad (22$$

where S is the gel strength at any time t, S' is the ultimate strength, and k is the gel rate constant. Figure 11 indicates that gel strength forms more rapidly at first then gradually approaches ultimate value as time elapsed. Equation 22 may be rewritten as:

$$\frac{t}{S} = \frac{t}{S'} + \frac{1}{S'k}$$

which indicates that a plot of t/S verses t should be a straight li Figure 11 represents the graph of t/S versus t, and indicates the slope the line is k and the y-intercept is 1/S'k. This approach provide means to evaluate the ultimate gel strength for each benton concentration. Table 2 represents the ultimate gel strengths and r constants for the five samples shown in Figures 11 and 12. Garrison a made measurements on similar suspensions at higher pH and determined t the ultimate strengths of the bentonite gels increased with e suspension as the pH increases. Table 3 reflects the pH - ultimate strength relationship observed.

Garrison also noted that the treating of muds with thinners had effect of decreasing the rate of gelling but not the ultimate strength. Thus it can be concluded that the reduced initial and 10 min gel strength will not be any less than that recorded for an untrea sample of the same mud. In fact, the ultimate gel strength may e increase as indicated in Table 2.

Garrison's work does not indicate that all muds comply with Equat 22, but it does point out that the initial and 10 minute gel strengths not provide a reliable means of predicting the ultimate gel st ng Weintritt and Hughes (1965) conducted progressive gel strength

FIGURE 10

INCREASE IN GEL STRENGTH OF
VARIOUS MUD TYPES WITH TIME
(FROM GRAY, DARLEY, AND ROGERS)

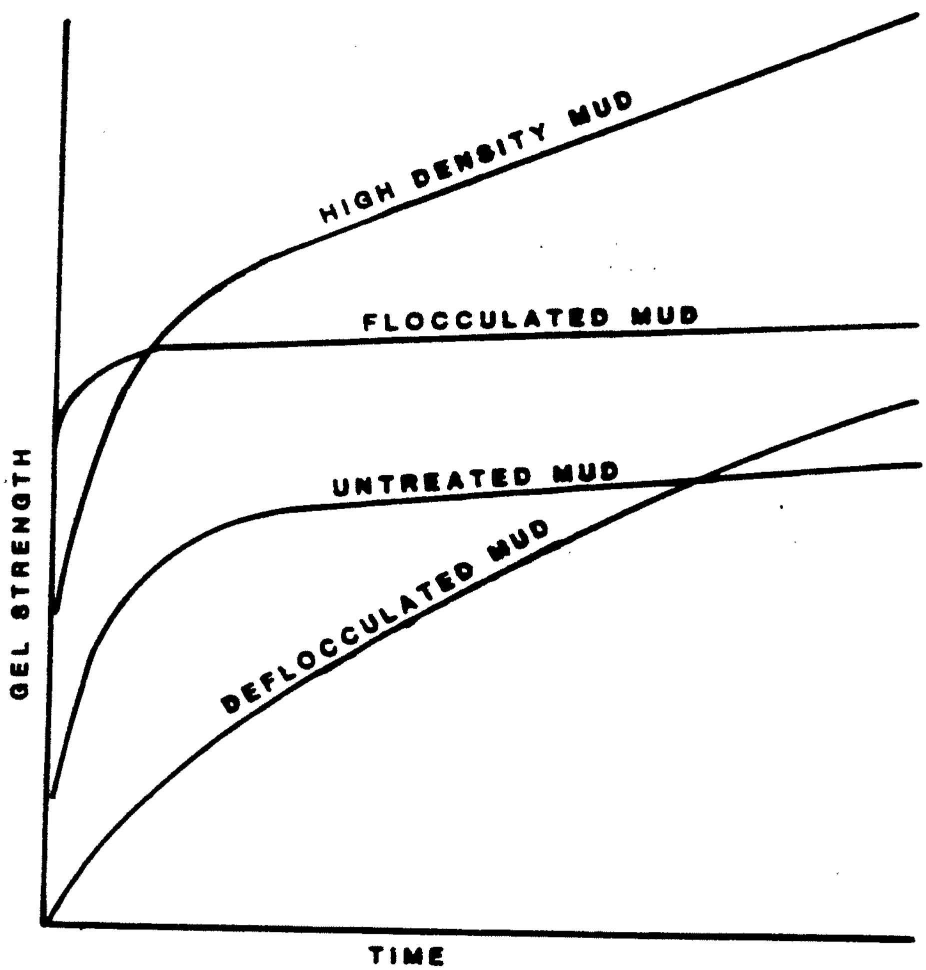


FIGURE 11
GEL STRENGTH IN RELATION TO TIME
AND RATE OF REACTION
(FROM GARRISON 1939)

SEE TABLE 2

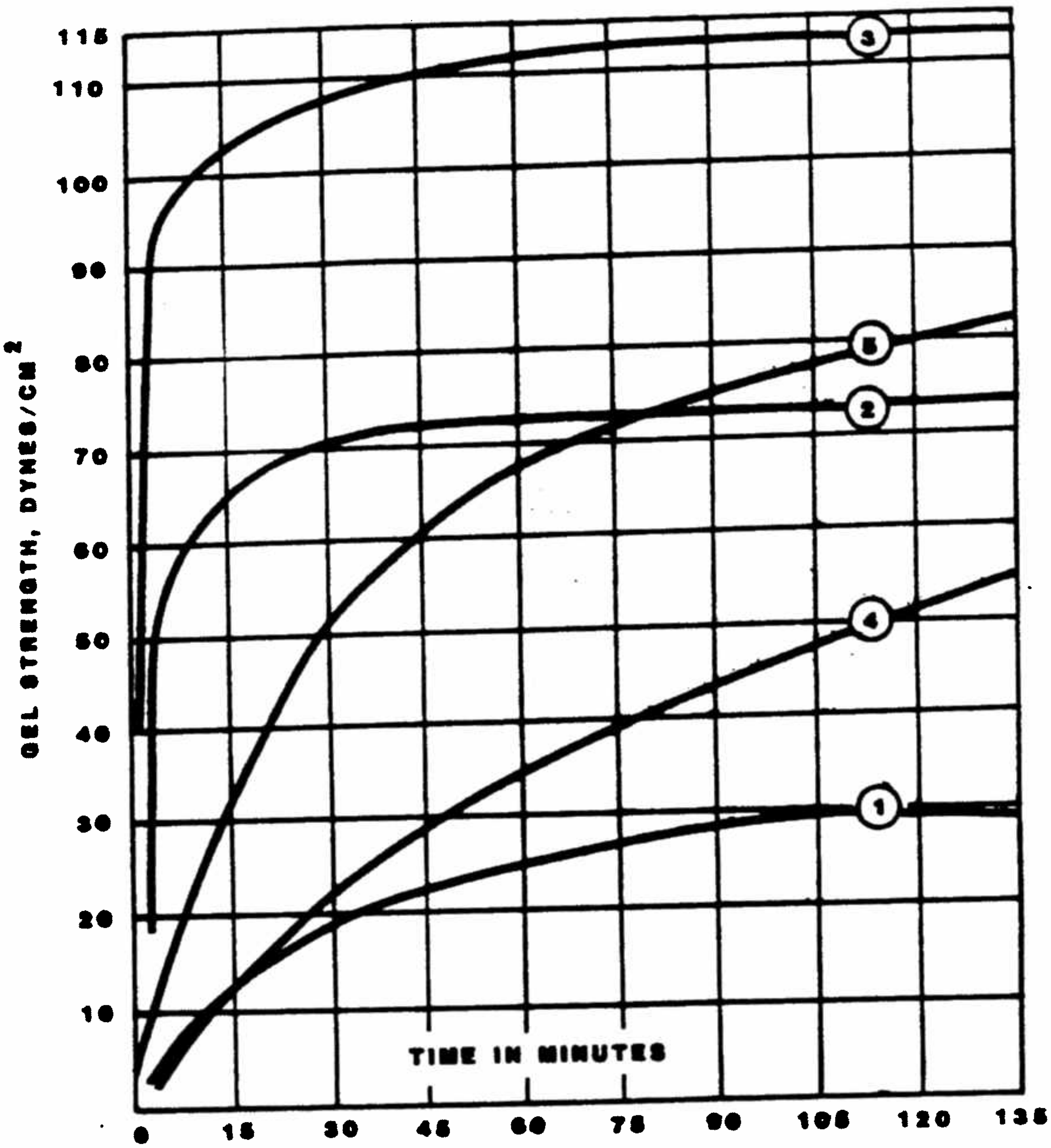


FIGURE 12

GEL STRENGTH AND RATE CONSTANTS
(FROM GARRISON 1939)
SEE TABLE 2

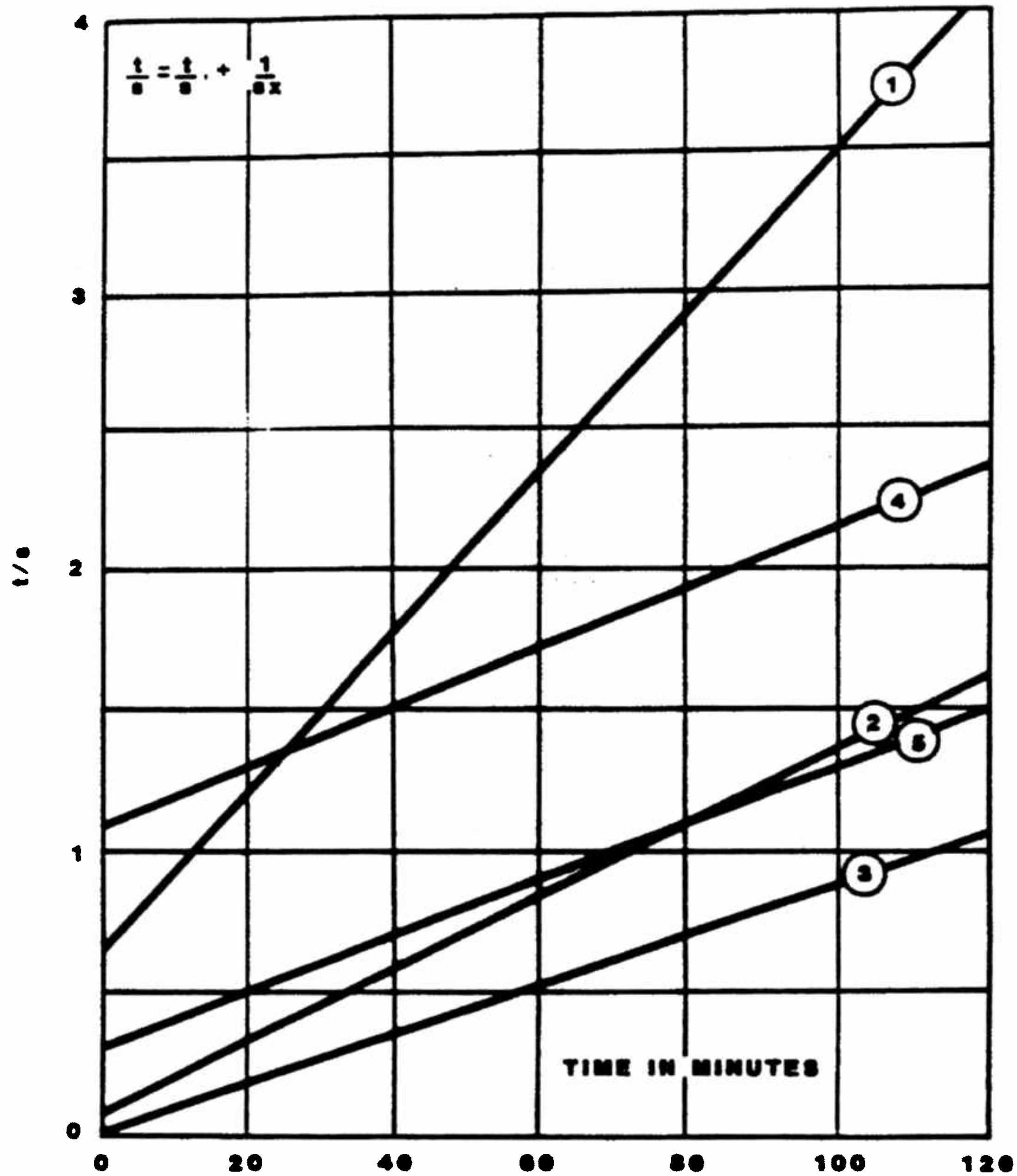


TABLE 2

GEL RATE CONSTANTS CALCULATED FROM FIGURES 11 AND 12

Bentonite Per Cent	Sample #	Additives	Gel Strength (Ultimate)	Rate Constant
4.5	1	---------	34.4	0.047
5.5	2	---------	74.4	0.75
6.5	3	---------	114.	0.79
5.5	4	0.1% Na Tannate	104.	0.0089
5.5	5	Sodium Hydroxide	99.7	0.033

(From Gray, Darley and Rogers)

TABLE 3

CONSTANTS IN GELLING EQUATIONS OF BENTONITE SUSPENSIONS

Bentonite Per Cent	Gel Strength and Rate Constant	pH+ 9.2	pH+ 9.3-9.5	pH+ 9.9-10	pH+ 10.8-11
4.5	S′	34.4	40.1	48.5	69.6
4.5	k	0.047	0.071	0.076	0.063
5.5	S′	74.4	32.2	129.9	152.7
5.5	k	0.75	0.22	0.13	0.18
6.5	S′	114.	141.	250.	268.
6.5	k	0.79	0.30	0.10	0.25

(From Garrison 1939)

ferrochrome lignosulfonate muds for periods up to 16 hours and obtained the results presented in Table 4. They noted that although Mud E and Mud F had similar properties, Mud F developed only a moderate gel strength while that of Mud E was much greater. Once again it is observed that the initial gel strength and 10 minute gel strength measurements are not always indicative of gel strength development which is observed at elevated temperatures and extended time. The three muds designated in Table 4 were obtained from wells within the same field just prior to cementing operations.

Annis (1976) noted that when a bentonite mud is quiescent, the gelling process depends on both temperature and time. Annis compared the effect of temperature on the initial and 30 minute gel strength of an 18 ppb bentonite suspension. Figure 13 indicates that the 30 minute gel strength of the 18 ppb suspension is at any temperature approximately six times the initial gel strength. The dependence of gel strength on time at different temperatures, as noted by Annis, is shown in Figure 14. Based on these and other tests of up to 18 hours Annis concluded that there is a strong indication that gel strength increases indefinitely with time.

Conclusion

In review, the above works indicate that the ultimate gel strength of water base muds is considerably higher than the values recorded for the initial and 10 minute gel strength. Although there is no direct relationship between gel strength and time, it is possible, based on available information, to conclude that the ultimate gel strength of a mud will be several times larger than the initial or 10 minute gel strength of the mud. In reference to the work by Garrison (1939), it is possible to consider the ultimate gel strength of a treated mud to be equivalent to that of a similar mud that was not treated, since the effect of the thinner is to decrease the rate of gelling and not the ultimate gel strength obtained.

In addition to time, temperature can have a major effect on the gel strength of water based drilling fluids. Srini-Vasan (1957) studied the effects of temperature on the gel strength of several water based drilling muds. Table 5 lists the muds which were tested and Figures 15 and 16 indicate the temperature versus gel strength relationships obtained. In most of the cases investigated by Srini-Vasan it was noted that the gel strength leveled off after 160°F. The emulsion and lime treated muds showed no change in gel strength with increase of temperature. It was found that each mud had its own characteristic curve and no quantitative interpretation was possible. The work of Weintritt and Hughes (1965) as noted in Table 4, indicates that emulsion Mud G experienced no change in gel strength in going from 75 to 180°F over a wide range of times. It is noted that although the gel strength did not vary with temperature, it went from an initial gel strength of 0 to a gel strength of 25 after 16 hours.

The equipment utilized by Srini-Vasan restricted his investigation to temperatures up to 220°F.

TABLE 4

COMPARISON OF MUD PROPERTIES WITH PROGRESSIVE GEL-STRENGTH TESTS
GYP-FERROCHROME LIGNOSULFONATE EMULSION MUDS

	SAMPLE			
	Mud E	Mud F	Mud G	
			No Treatment	3 lb/bbl PCL
Weight, unstirred, lb/gal	11.0	10.7	10.6	
Weight, stirred, lb/gal	11.0	10.3	10.7	
Plastic Viscosity, cp	14	23	16	15
Yield Point, lb/100 sq ft	3	6	2	1
10-sec gel, lb/100 sq ft	1	2	1	0
10-min gel, lb/100 sq ft	8	8	7	3
API filtrate, sl	6.2	3.3	5.2	2.9
pH	10.9	10.6	10.5	10.4
Composition: Water, % by vol	76	63	75	
Oil, % by vol	5	11	9	
Solids, % by vol	19	16	16	
Solids, % by wt	39	36	37	
Solids, SG	2.7	2.9	3.0	
Filtrate Ion Analysis:				
Chlorides ppm	**3500**	**400**	**3000**	
Sulfate, epm	**250**	**300**	**130**	
Carbonate, epm	**24**	**28**	**12**	
Bicarbonate, epm	**12**	**160**	**12**	
Calcium, epm	**44**	**52**	**44**	

Progressive Gel Strengths lb/100 sq ft	**Temperature (°F)**							
Time	75°	180°	75°	180°	75°	180°	75°	180°
0 **minutes**	1	1	2	2	1	1	0	0
3 **minutes**	2	3	2	5	3	8	1	1
10 **minutes**	8	18	8	12	7	26	3	3
30 **minutes**	15	40	11	18	17	58	5	5
60 **minutes**	27	90	18	16	29	91	6	6
2 hours	31	145	22	22	29	104	7	7
4 hours	37	190	29	42	46	172	10	10
8 hours	46	190	33	42				
16 hours	80	320	40	57	95	320	25	2

(From Weintritt and Hughes 1965)

FIGURE 13

EFFECT OF TEMPERATURE ON INITIAL
AND 30-MINUTE GEL STRENGTH
(FROM ANNIS 1976)

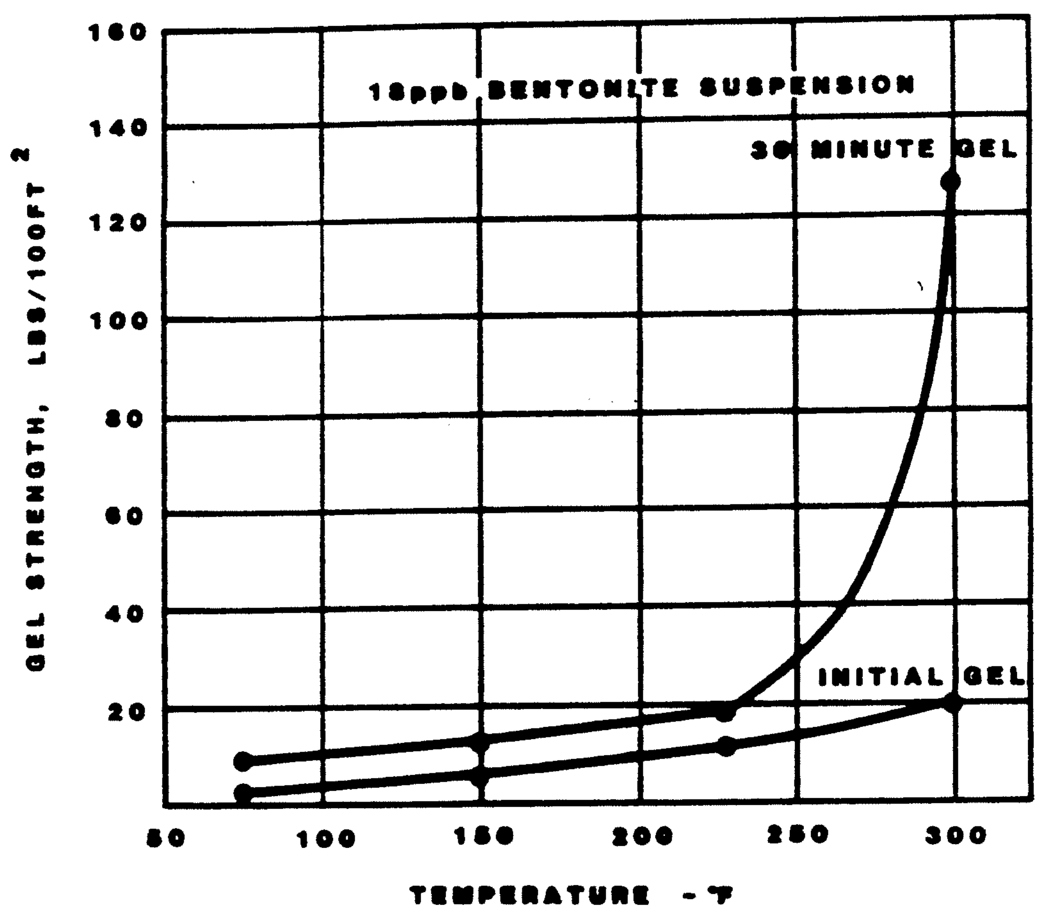


FIGURE 14
EFFECTS OF TIME AND TEMPERATURE
ON GEL STRENGTH
(FROM ANNIS 1976)

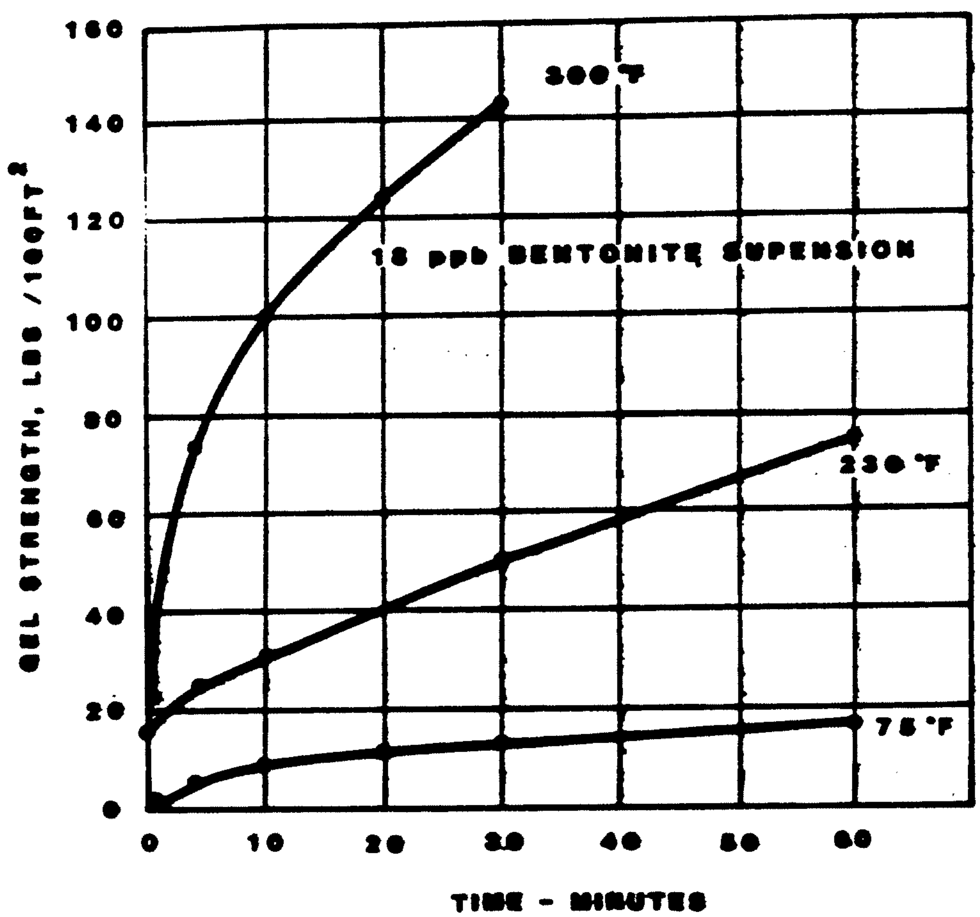


TABLE 5

COMPOSITION OF THE MUD SAMPLES TESTED FOR GEL STRENTGH

SAMPLE NUMBER	COMPOSITION OF THE MUD**
33	2 per cent bentonite mud
34	3 per cent bentonite mud
35	4 per cent bentonite mud
39	10 lb/gal, 4 per cent bentonite, barite mud
43	10 lb/gal, 10 per cent (by volume) Diesel oil, 4 percent bentonite, barite, emulsion mud
47	10 lb/gal, 4 per cent bentonite, barite, surfactant (DMS) mud
49	10 lb/gal, low lime (1 lb/bbl) treated, 4 per cent bentonite, barite mud

**All muds referred to are water base muds.
All per cent quantities mentioned denote weight per cents, unless otherwise designated.

(From Srini-Vasan)

TABLE 6

GEL STRENGTH OF A 4 PERCENT SUSPENSION OF PURE SODIUM MONTMORILLONITE TO WHICH AN EXCESS OF 50 MEQ/LITER OF NaOH HAS BEEN ADDED, MEASURED AT VARIOUS TEMPERATURES AND PRESSURES

t(°F)	P(psi)	Gel Strength (lb/100 sq ft) 1 min	10 min	30 min
78	300	2.2	—	35.0
	8000	2.2	—	7.0
212	300	18.0	26.0	40.0
	8000	9.0	9.0	15.0
302	300	240.0	290.0	265.0
	8000	88.0	100.0	100.0

(From Hiller 1963)

FIGURE 15
GEL STRENGTH VERSUS TEMPERATURE FOR
BENTONITE-WATER MUDS (FROM SRINI-VASAN 1957)

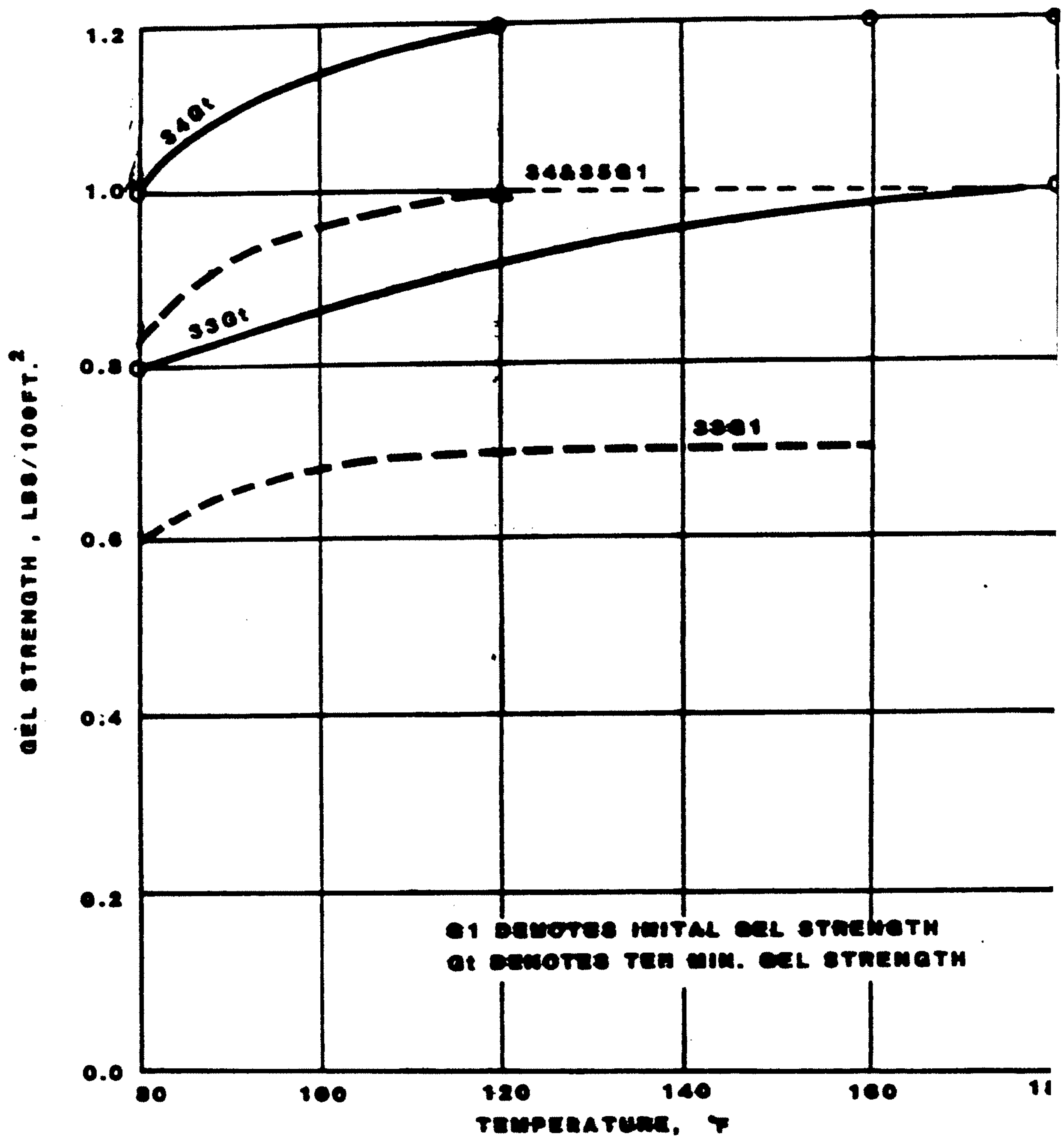
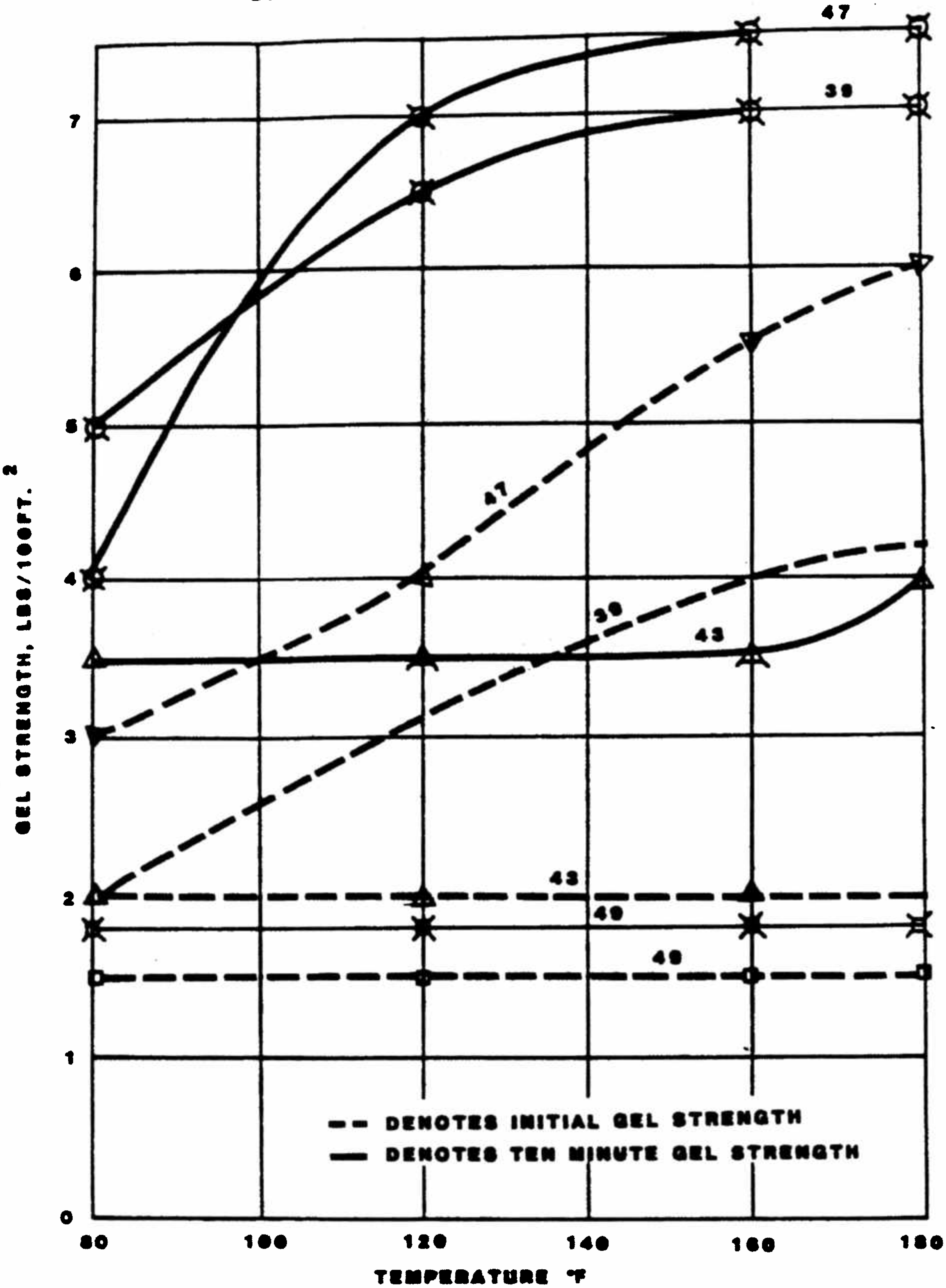


FIGURE 16

GEL STRENGTH VERSUS TEMPERATURE FOR DIFFERENT MUDS (FROM SRINI-VASAN 1957)



Annis (1976) was capable of investigating the gel strength up to temperatures of 350°F. Srini-Vasan observed that the gel strengths leveled off after 160°F but Annis noted that at higher temperature a rapid increase in the gel strength was noted. Figure 17 reflects this observation. Thus increased temperature, like increased bentonite concentration promotes flocculation. The temperature at which a rapid increase in gel strength occurs, represents the onset of flocculation. Therefore it is possible to expect the gel strength to increase significantly at some elevated temperature.

Annis studied the gel strength properties of about 40 water base field muds at temperatures ranging to 300°F. The muds covered a wide range of densities and mud types, although the majority were lignosulfonate muds. To draw conclusions on the effects of high temperature on gel strength, the gel strength properties were averaged and are presented in Figure 18.

Hiller (1963) noted that some clay suspensions display a decrease in gel strength with increased pressure, especially at high temperatures. It was noted that the gel strength was reduced to 1/4 of its original value for a pressure increase from 300 to 8000 psi at a temperature of 302°F. This reduction in the gel strength resulting from increased pressure is presented in Table 6.

Although no direct means exists to determine the ultimate gel strength of a drilling mud at borehole conditions, it is possible to safely say that the gel strength developed in the borehole is considerably greater than that indicated by the initial and 10 minute gel strengths recorded for a given mud. The effects of time, temperature and pressure on the gel strength of the static mud column have been discussed above. In the range of pressures and temperatures normally encountered in disposal formations, pressure should exert a negligible effect on the gel strength. Flocculation at high temperature should not occur except in the deepest of disposal formations. Certain muds do not display a temperature dependence, but the effect of time is ever present.

The research discussed above investigated muds with 0 initial gel strength to ultimate gel strengths of 100's lbs/100SF. In an attempt to select a minimum ultimate gel strength that could be expected for the worst of mud and borehole conditions, a value of 20 lbs/100 ft^2 should be utilized for the ultimate gel strength in all gel strength pressure calculations where actual numbers are not available. This value will provide a considerable safety factor in most cases.

The 20 lb/100 ft^2 ultimate gel strength was arbitrarily selected to insure that a sufficient safety factor is built into the proposed procedure. The selection is the result of individual judgment prejudiced by the above discussion."

FIGURE 17

EFFECTS OF TEMPERATURE AND BENTONITE
CONCENTRATION ON 30 MINUTE GEL STRENGTH
(FROM ANNIS 1976)

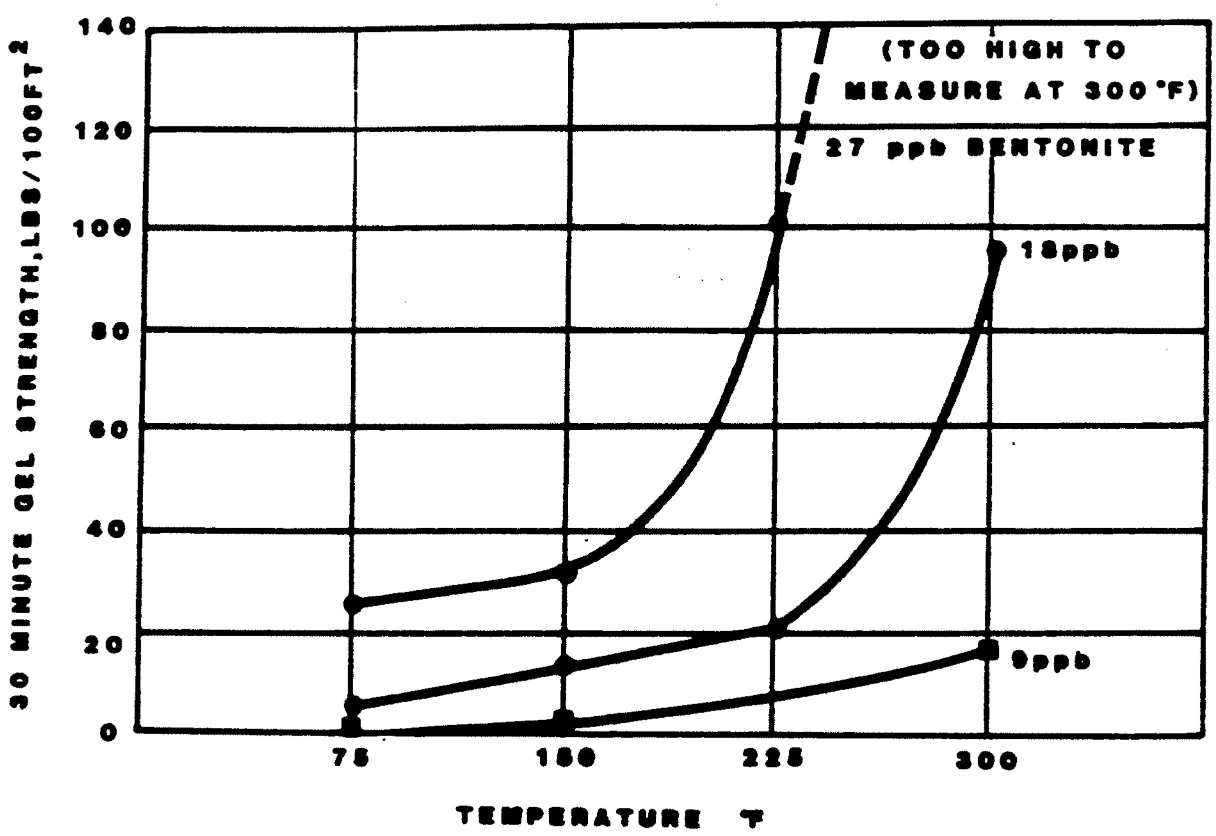
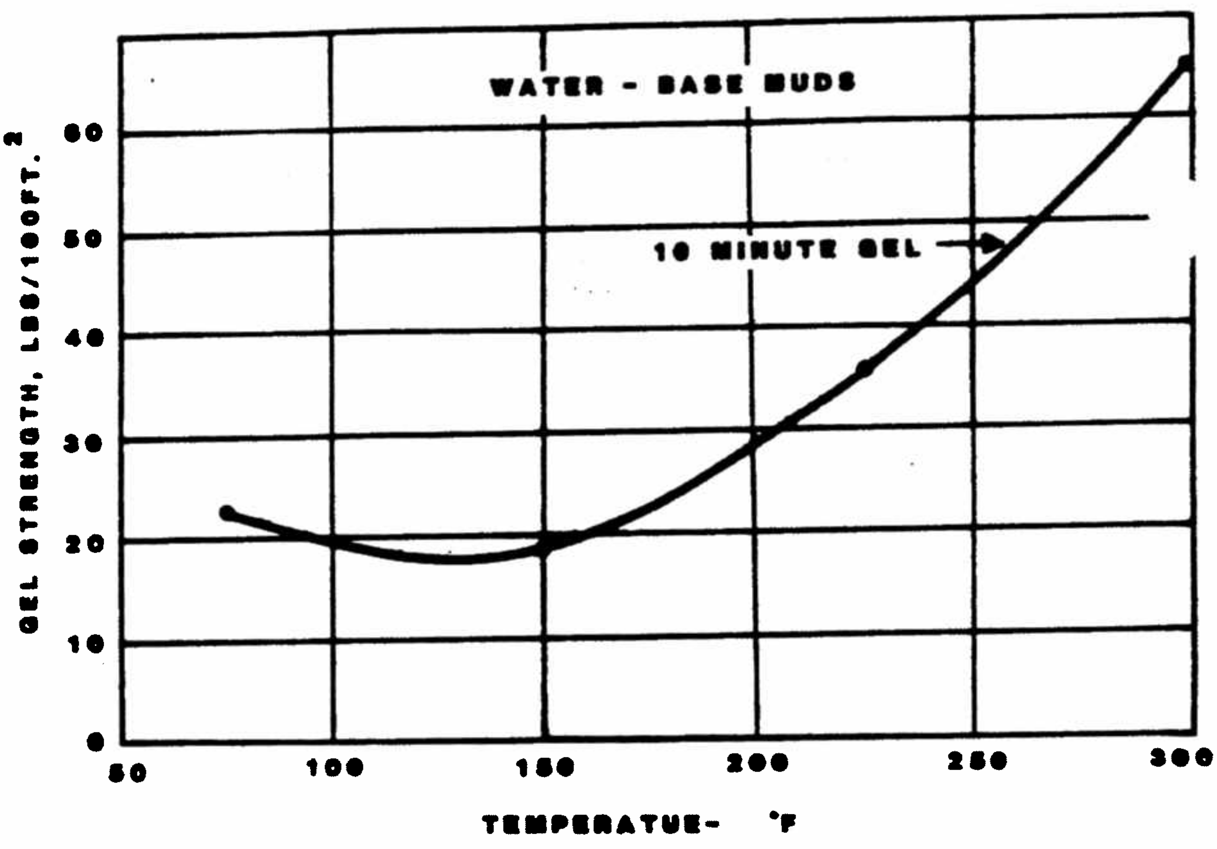


FIGURE 18

EFFECT OF TEMPERATURE ON 10 -MINUTE GEL STRENGTH (FROM ANNIS 1976)



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Ken E. Davis, President of Ken E. Davis Associates, 3121 San Jacinto, Suite 102, Houston, Texas 77004, has extensive experience in the field of injection well systems used for secondary recovery disposal and storage. He has either personally installed or been responsible for the installation of over fifty (50) Industrial Disposal Wells and over one hundred (100) Salt Water Disposal Wells in the continental United States, Europe and Mexico. He has also worked as technical advisor to the Environmental Protection Agency on their Underground Injection Control Program authorized by the Safe Drinking Water Act, The Department of Energy on their various Underground Storage Programs and The Bureau of Reclamation on their various salinity control projects.

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DEQ OF LOUISIANA, 2009

APPENDIX 4 TO THE 2009 TRIENNIAL SUMMARY REPORT

IN THE EVANGELINE SUMMARY REPORT, 2007

EVANGELINE AQUIFER SUMMARY, 2007

AQUIFER SAMPLING AND ASSESSMENT PROGRAM

DEQ
LOUISIANA

APPENDIX 4 TO THE 2009 TRIENNIAL SUMMARY REPORT

PARTIAL FUNDING PROVIDED BY THE CWA

ASSET
AQUIFER SAMPLING AND ASSESSMENT PROGRAM

Contents

BACKGROUND

The Louisiana Department of Environmental Quality's (LDEQ) Aquifer Sampling and Assessment Program (ASSET) is an ambient monitoring program established to determine and monitor the quality of ground water produced from Louisiana's major freshwater aquifers. The ASSET Program samples approximately 200 water wells located in 14 aquifers and aquifer systems across the state. The sampling process is designed so that all fourteen aquifers and aquifer systems are monitored on a rotating basis, within a three-year period so that each well is monitored every three years.

In order to better assess the water quality of a particular aquifer, an attempt is made to sample all ASSET Program wells producing from it in a narrow time frame. To more conveniently and economically promulgate those data collected, a summary report on each aquifer is prepared separately. Collectively, these aquifer summaries will make up, in part, the ASSET Program's Triennial Summary Report for 2009.

Analytical and field data contained in this summary were collected from wells producing from the Evangeline aquifer, during the 2007 state fiscal year (July 1, 2006 - June 30, 2007). This summary will become Appendix 4 of ASSET Program Triennial Summary Report for 2009.

These data show that in January and February of 2007, and in May 2008, 12 wells were sampled which produce from the Evangeline aquifer. Eight of these 12 are classified as public supply, while there are one each classified by the Louisiana Department of Transportation and Development (LDOTD) as irrigation, industrial, domestic and other. The wells are located in 7 parishes from the central and southwest areas of the state.

Figure 4-1 shows the geographic locations of the Evangeline aquifer and the associated wells, whereas Table 4-1 lists the wells in the aquifer along with their total depths, use made of produced waters and date sampled.

Well data for registered water wells were obtained from the Louisiana Department of Transportation and Development's Water Well Registration Data file.

GEOLOGY

The Evangeline aquifer is comprised of unnamed Pliocene sands and the Pliocene-Miocene Blounts Creek member of the Fleming formation. The Blounts Creek consists of sands, silts, and silty clays, with some gravel and lignite. The sands of the aquifer are moderately well to well sorted and fine to medium grained with interbedded coarse sand, silt, and clay. The mapped outcrop corresponds to the outcrop of the Blounts Creek member, but downdip, the aquifer thickens and includes Pliocene sand beds that do not outcrop. The confining clays of the Castor Creek member (Burkeville aquiclude) retard the movement of water between the Evangeline and the underlying Miocene aquifer systems. The Evangeline is separated in most areas from the overlying Chicot aquifer by clay beds; in some areas the clays are missing and the upper sands of the Evangeline are in direct contact with the lower sands and gravels of the Chicot.

HYDROGEOLOGY

Recharge to the Evangeline aquifer occurs by the direct infiltration of rainfall in interstream, upland outcrop areas and the movement of water through overlying terrace deposits, as well as leakage from other aquifers. Fresh water in the Evangeline is separated from water in stratigraphically equivalent deposits in southeast Louisiana by a saltwater ridge in the Mississippi River valley. The hydraulic conductivity of the Evangeline varies between 20 and 100 feet/day.

The maximum depths of occurrence of freshwater in the Evangeline range from 150 feet above sea level, to 2,250 feet below sea level. The range of thickness of the fresh water interval in the Evangeline is 50 to 1,900 feet. The depths of the Evangeline wells that were monitored in conjunction with the BMP range from 170 to 1,715 feet.

PROGRAM PARAMETERS

The field parameters checked at each ASSET well sampling site and the list of conventional parameters analyzed in the laboratory are shown in Table 4-2. The inorganic (total metals) parameters analyzed in the laboratory are listed in Table 4-3. These tables also show the field and analytical results determined for each analyte. For quality control, duplicate samples were taken for each parameter at wells CU-1362 and EV-858.

In addition to the field, conventional and inorganic analytical parameters, the target analyte list includes three other categories of compounds: volatiles, semi-volatiles, and pesticides/PCBs. Due to the large number of analytes in these categories, tables were not prepared showing the analytical results for these compounds. A discussion of any detections from any of these three categories, if necessary, can be found in their respective sections. Tables 4-8, 4-9 and 4-10 list the target analytes for volatiles, semi-volatiles and pesticides/PCBs, respectively.

Tables 4-4 and 4-5 provide a statistical overview of field and conventional data, and inorganic data for the Evangeline aquifer, listing the minimum, maximum, and average results for these parameters collected in the FY 2007 sampling. Tables 4-6 and 4-7 compare these same parameter averages to historical ASSET-derived data for the Evangeline aquifer, from fiscal years 1995, 1998, 2001 and 2004.

The average values listed in the above referenced tables are determined using all valid, reported results, including non-detects. Per Departmental policy concerning statistical analysis, one-half of the detection limit (DL) is used in place of zero when non-detects are encountered. However, the minimum value is reported as less than the DL, not one-half the DL. If all values for a particular analyte are reported as non-detect, then the minimum, maximum, and average values are all reported as less than the DL. For contouring purposes, one-half the DL is also used for non-detects in the figures and charts referenced below.

Figures 4-2, 4-3, 4-4, and 4-5, respectively, represent the contoured data for pH, total dissolved solids (TDS), chloride (Cl) and iron. Charts 4-1 through 4-16 represent the trend of the graphed parameter, based on the averaged value of that parameter for each three-year reporting period.

Discussion of historical data and related trends is found in the **Water Quality Trends and Comparison to Historical ASSET Data** section.

INTERPRETATION OF DATA

Under the Federal Safe Drinking Water Act, EPA has established maximum contaminant levels (MCLs) for pollutants that may pose a health risk in public drinking water. An MCL is the highest level of a contaminant that EPA allows in public drinking water. MCLs ensure that drinking water does not pose either a short-term or long-term health risk. While not all wells sampled were public supply wells, the Office of Environmental Assessment does use the MCLs as a benchmark for further evaluation.

EPA has set secondary standards, which are defined as non-enforceable taste, odor, or appearance guidelines. Field and laboratory data contained in Tables 4-2 and 4-3 show that one secondary MCL (SMCL) was exceeded in 7 of the 12 wells sampled in the Evangeline aquifer.

Field and Conventional Parameters

Table 4-2 shows the field and conventional parameters for which samples are collected at each well and the analytical results for those parameters. Table 4-4 provides an overview of this data for the Evangeline aquifer, listing the minimum, maximum, and average results for these parameters.

Federal Primary Drinking Water Standards: A review of the analysis listed in Table 4-2 shows that no primary MCL was exceeded for field or conventional parameters for this reporting period. Those ASSET wells reporting turbidity levels greater than 1.0 NTU do not exceed the Primary MCL of 1.0, as this standard applies to public supply water wells that are under the direct influence of surface water. The Louisiana Department of Health and Hospitals has determined that no public water supply well in Louisiana was in this category.

Federal Secondary Drinking Water Standards: A review of the analysis listed in Table 4-2 shows that four wells exceeded the SMCL for pH, and two wells exceeded the SMCL for total dissolved solids. Laboratory results override field results in exceedance determinations, thus only lab results will be counted in determining SMCL exceedance numbers for TDS. Following is a list of SMCL parameter exceedances with well number and results:

pH (SMCL = 6.5 – 8.5 Standard Units):

AL-120 – 8.68 SU
AL-363 –9.20 SU
BE-512 – 8.96 SU
V-668 – 8.73 SU

Total Dissolved Solids (SMCL = 500 mg/L or 0.5 g/L):

	LAB RESULTS (in mg/L)	FIELD MEASURES (in g/L)
AV-441	730 mg/L	0.68 g/L
EV-858	738 mg/L, Duplicate – 724 mg/L	0.76 g/L (Original and Duplicate)

Inorganic Parameters

Table 4-3 shows the inorganic (total metals) parameters for which samples are collected at each well and the analytical results for those parameters. Table 4-5 provides an overview of inorganic data for the Evangeline aquifer, listing the minimum, maximum, and average results for these parameters.

Federal Primary Drinking Water Standards: A review of the analyses listed on Table 4-3 shows that no primary MCL was exceeded for total metals.

Federal Secondary Drinking Water Standards: Laboratory data contained in Table 4-3 shows that one well exceeded the secondary MCL for iron:

Iron (SMCL = 300 ug/L):

CU-1362 – 367 ug/L, Duplicate – 363 ug/L

Volatile Organic Compounds

Table 4-8 shows the volatile organic compound (VOC) parameters for which samples are collected at each well. Due to the number of analytes in this category, analytical results are not tabulated; however any detection of a VOC would be discussed in this section.

Chloroform was detected in well AL-373 at 2.06 ug/L, which is just over the laboratory detection limit of 2 ug/L for this compound. Because chloroform was detected at this low concentration, and due to there being no MCL established for this compound, and because chloroform is a common lab contaminant, the well was not resampled to confirm the occurrence of chloroform. The well owner was given a report of these results and close attention will be given to this well in upcoming regular sampling activities. No other VOC was detected at or above its respective detection limit during the FY 2007 sampling of the Evangeline aquifer.

Semi-Volatile Organic Compounds

Table 4-9 shows the semi-volatile organic compound (SVOC) parameters for which samples are collected at each well. Due to the number of analytes in this category, analytical results are not tabulated; however any detection of a SVOC would be discussed in this section.

There were no confirmed detections of a SVOC at or above its detection limit during the FY 2007 sampling of the Evangeline aquifer.

Pesticides and PCBs

Table 4-10 shows the pesticide and PCB parameters for which samples are collected at each well. Due to the number of analytes in this category, analytical results are not tabulated; however any detection of a pesticide or PCB would be discussed in this section.

There were no confirmed detections of a pesticide or PCB at or above its detection limit during the FY 2007 sampling of the Evangeline aquifer.

WATER QUALITY TRENDS AND COMPARISON TO HISTORICAL ASSET DATA

Analytical and field data show that the quality and characteristics of ground water produced from the Evangeline aquifer exhibit some changes when comparing current data to that of the four previous sampling rotations (three, six, nine and twelve years prior). These comparisons can be found in Tables 4-6 and 4-7, and in Charts 4-1 to 4-16 of this summary. Over the twelve-year period data averages show that 6 analytes have shown a general increase in concentration. These analytes are: pH, chloride, sulfate, hardness, barium, and iron. For this same time period, the average concentrations for 8 analytes have demonstrated a decrease. These are: temperature, specific conductance (field and lab), salinity, total dissolved solids, TKN, total phosphorus, copper, and zinc. The average ammonia concentration has been consistent for this time period while the average for nitrite-nitrate has been consistently below its detection limit for each reporting period.

The current number of wells with secondary MCL exceedances is the same as the previous sampling event in FY 2004, with 7 wells reporting at least one exceedance each. However, for the FY 2007 reporting period, there were fewer total SMCLs exceeded, with 7 exceedances in FY 2007 and 10 exceedances in FY 2004.

SUMMARY AND RECOMMENDATIONS

In summary, the data show that the ground water produced from this aquifer is generally soft[1] and is of good quality when considering short-term or long-term health risk guidelines. Laboratory data show that no well that was sampled for this reporting period exceeded a primary MCL. The data also show that this aquifer is of good quality when considering taste, odor, or appearance guidelines. A comparison to historical ASSET data show that 6 analytes have increased in their average concentrations, 8 have decreased, and 2 have remained constant or below its detection limit.

It is recommended that the ASSET wells assigned to the Evangeline aquifer be re-sampled as planned in approximately three years. In addition, several wells should be added to the 11 currently in place to increase the well density for this aquifer.

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[1] Classification based on hardness scale from: Peavy, H.S. et al. *Environmental Engineering.* New York: McGraw-Hill. 1985.

Table 4-1: List of Wells Sampled, Evangeline Aquifer–FY 2007

DOTD Well Number	Parish	Date	Owner	Depth (Feet)	Well Use
AL-120	ALLEN	1/30/2007	CITY OF OAKDALE	910	PUBLIC SUPPLY
AL-363	ALLEN	1/29/2007	WEST ALLEN PARISH WATER DIST.	1715	PUBLIC SUPPLY
AL-373	ALLEN	5/19/2008	TOWN OF OBERLIN	747	PUBLIC SUPPLY
AL-391	ALLEN	1/30/2007	FAIRVIEW WATER SYSTEM	800	PUBLIC SUPPLY
AV-441	AVOYELLES	1/30/2007	TOWN OF EVERGREEN	319	PUBLIC SUPPLY
BE-410	BEAUREGARD	1/29/2007	BOISE CASCADE	474	INDUSTRIAL
BE-512	BEAUREGARD	1/29/2007	SINGER WATER DISTRICT	918	PUBLIC SUPPLY
CU-1362	CALCASIEU	2/14/2007	LA WATER CO	635	PUBLIC SUPPLY
EV-858	EVANGELINE	1/29/2007	SAVOY SWORDS WATER SYSTEM	472	PUBLIC SUPPLY
R-1350	RAPIDES	1/30/2007	PRIVATE OWNER	180	IRRIGATION
V-5065Z	VERNON	1/30/2007	PRIVATE OWNER	170	DOMESTIC
V-668	VERNON	1/30/2007	LDWF/FORT POLK WMA HQ	280	OTHER

Table 4-2: Summary of Field and Conventional Data, Evangeline Aquifer–FY 2007

DOTD WELL NUMBER	Temp Deg. C	pH SU	Sp. Cond. mmhos/cm	Sal. ppt	TDS g/L	Alk mg/L	Cl mg/L	Color PCU	Sp. Cond. umhos/cm	SO4 mg/L	TDS mg/L	TSS mg/L	Turb. NTU	NH3 mg/L	Hard. mg/L	Nitrite-Nitrate (as N) mg/L	TKN mg/L	Tot. P mg/L
	LABORATORY DETECTION LIMITS →					2.0	1.3	5	10	1.25/1.3	4	4	1	0.1	5.0	0.05	0.10	0.05
	FIELD PARAMETERS					LABORATORY PARAMETERS												
AL-120	23.17	8.68	0.337	0.16	0.22	157	3.4	Not Analyzed by Lab	309	6.2	205	<4	<1	<0.1	<5	<0.05	<0.1	0.13
AL-363	26.85	9.20	0.516	0.25	0.34	265	2.9		492	1.9	304	<4	<1	0.13	<5	<0.05	0.14	0.28
AL-373	23.40	7.82	0.323	0.15	0.21	157	10		324	2.1	213	<4	1	<0.1	<5	0.06	0.14	0.33
AL-391	22.12	8.29	0.275	0.13	0.18	118	4		235	5.4	160	<4	<1	0.2	36	<0.05	0.27	0.09
AV-441	20.16	8.07	1.048	0.52	0.68	428	92.9		1,144	39.8	730	<4	<1	0.44	13.2	<0.05	0.65	0.14
BE-410	21.45	8.06	0.211	0.10	0.14	85.8	4.8		182	2.6	131	<4	<1	<0.1	60.9	0.06	<0.1	<0.05
BE-512	24.11	8.96	0.35	0.17	0.23	166	4.3		322	5.8	204	<4	<1	<0.1	5	<0.05	<0.1	0.1
CU-1362	22.71	6.87	0.323	0.15	0.21	122	14		271	2	201	<4	<1	0.12	35.7	<0.05	0.16	0.25
CU-1362*	22.71	6.87	0.323	0.15	0.21	122	14.3		272	2	200	<4	<1	0.1	35.8	<0.05	0.1	0.25
EV-858	21.35	7.73	1.176	0.59	0.76	388	‡181		1,252	<1.3	738	<4	<1	0.74	83.3	<0.05	0.82	0.22
EV-858*	21.35	7.73	1.176	0.59	0.76	390	‡180		1,260	<1.3	724	<4	<1	0.71	81.9	<0.05	0.83	0.23
R-1350	19.87	7.92	0.12	0.06	0.08	22.5	3.4		68.8	‡5.6	95.3	<4	2	<0.1	8.2	<0.05	<0.1	0.06
V-5065Z	13.82	7.87	0.128	0.06	0.08	29.1	4.7		73	<1.3	79.3	<4	<1	<0.1	15.5	<0.05	0.12	0.06
V-668	9.79	8.73	0.089	0.04	0.06	10.5	3		34.7	<1.3	50	<4	1.1	<0.1	8.3	<0.05	<0.1	<0.05

*Denotes Duplicate Sample ‡Reported from a Dilution Shaded cells exceed EPA Secondary Standards

Table 4-3: Summary of Inorganic Data, Evangeline Aquifer–FY 2007

DOTD Well Number	Antimony ug/L	Arsenic ug/L	Barium ug/L	Beryllium ug/L	Cadmium ug/L	Chromium ug/L	Copper ug/L	Iron ug/L	Lead ug/L	Mercury ug/L	Nickel ug/L	Selenium ug/L	Silver ug/L	Thallium ug/L	Zinc ug/L
Laboratory Detection Limits	1	3	2	1	0.5	5	3	20	3	0.05	3	4	0.5	1	10
AL-120	<1	3.1	9.1	<1	<0.5	<3	<3	20.8	<3	<0.05	<3	<4	<0.5	<1	<10
AL-363	<1	3	9.1	<1	<0.5	<3	<3	24.8	<3	<0.05	<3	<4	<0.5	<1	<10
AL-373	<1	<3	11.8	<1	<0.5	<3	9.3	237	<3	*0.09	<3	<4	<0.5	<1	60.2
AL-391	<1	<3	124	<1	<0.5	<3	<3	50.5	<3	<0.05	<3	<4	<0.5	<1	<10
AV-441	<1	<3	71.5	<1	<0.5	<3	<3	232	<3	<0.05	<3	<4	0.6	<1	<10
BE-410	<1	3.5	150	<1	<0.5	<3	<3	<20	<3	<0.05	<3	<4	<0.5	<1	<10
BE-512	<1	3.3	15.7	<1	<0.5	<3	<3	<20	<3	<0.05	<3	<4	<0.5	<1	<10
CU-1362	<1	R	183	<1	<0.5	<3	3.4	367	<3	<0.05	<3	<4	<0.5	<1	12.6
CU-1362*	<1	R	181	<1	<0.5	<3	3.1	363	<3	<0.05	<3	<4	<0.5	<1	10.8
EV-858	<1	<3	455	<1	<0.5	<3	<3	165	<3	<0.05	<3	<4	<0.5	<1	<10
EV-858*	<1	<3	451	<1	<0.5	<3	<3	161	<3	<0.05	<3	<4	<0.5	<1	<10
R-1350	<1	<3	14.4	<1	<0.5	<3	<3	752	<3	<0.05	<3	<4	<0.5	<1	56.8
V-5065Z	<1	<3	73.8	<1	<0.5	<3	5.9	<20	<3	<0.05	<3	<4	<0.5	<1	17.8
V-668	<1	<3	41.6	<1	<0.5	<3	12.7	88.3	<3	<0.05	<3	<4	<0.5	<1	18.2

*Denotes Duplicate Sample.　　“R” = Data rejected, arsenic detected in Field Blank　　Shaded cells exceed EPA Secondary Standards

Table 4-4: FY 2007 Field and Conventional Statistics, ASSET Wells

	PARAMETER	MINIMUM	MAXIMUM	AVERAGE
FIELD	Temperature (^{O}C)	19.87	26.85	22.44
	pH (SU)	6.87	9.20	8.06
	Specific Conductance (mmhos/cm)	0.089	1.176	0.460
	Salinity (ppt)	0.04	0.59	0.22
	TDS (g/L)	0.058	0.764	0.300
LABORATORY	Alkalinity (mg/L)	10.5	428.0	175.8
	Chloride (mg/L)	2.9	181.0	37.3
	Specific Conductance (umhos/cm)	34.7	1,260.0	445.7
	Sulfate (mg/L)	<1.3	39.8	5.4
	TDS (mg/L)	50	738	289
	TSS (mg/L)	<4	<4	<4
	Turbidity (NTU)	<1	2	<1
	Ammonia, as N (mg/L)	<0.1	0.74	0.20
	Hardness (mg/L)	<5	83.3	27.9
	Nitrite - Nitrate, as N (mg/L)	<0.05	0.06	<0.05
	TKN (mg/L)	<0.1	0.83	0.25
	Total Phosphorus (mg/L)	<0.05	0.33	0.16

Table 4-5: FY 2007 Inorganic Statistics, ASSET Wells

PARAMETER	MINIMUM	MAXIMUM	AVERAGE
Antimony (ug/L)	<1	<1	<1
Arsenic (ug/L)	<3	3.5	<3
Barium (ug/L)	9.1	455.0	127.9
Beryllium (ug/L)	<1	<1	<1
Cadmium (ug/L)	<0.5	<0.5	<0.5
Chromium (ug/L)	<3	<3	<3
Copper (ug/L)	<3	12.7	3.4
Iron (ug/L)	<20	752	178
Lead (ug/L)	<3	<3	<3
Mercury (ug/L)	<0.05	<0.05	<0.05
Nickel (ug/L)	<3	<3	<3
Selenium (ug/L)	<4	<4	<4
Silver (ug/L)	<0.5	0.6	<0.5
Thallium (ug/L)	<1	<1	<1
Zinc (ug/L)	<10	60.2	15.5

Table 4-6: Triennial Field and Conventional Statistics, ASSET Wells

	PARAMETER	FY 1995 AVERAGE	FY 1998 AVERAGE	FY 2001 AVERAGE	FY 2004 AVVERAGE	FY 2007 AVERAGE
FIELD	Temperature (^{O}C)	23.71	22.87	21.33	22.69	22.44
	pH (SU)	7.14	7.08	7.05	7.54	8.06
	Specific Conductance (mmhos/cm)	0.50	0.50	0.30	0.32	0.46
	Salinity (ppt)	0.22	0.21	0.14	0.15	0.22
	TDS (g/L)	-	-	-	0.21	0.30
LABORATORY	Alkalinity (mg/L)	205.8	192.8	176.7	137.2	175.8
	Chloride (mg/L)	15.2	27.0	38.3	18.1	37.3
	Color (PCU)	23.3	6.7	8.2	7.5	-
	Specific Conductance (umhos/cm)	489.6	453.8	446.1	322.3	445.7
	Sulfate (mg/L)	4.71	4.40	5.73	5.43	5.4
	TDS (mg/L)	308.4	324.8	263.7	209.4	289
	TSS (mg/L)	<4	<4	<4	<4	<4
	Turbidity (NTU)	<1	<1	<1	1.04	<1
	Ammonia, as N (mg/L)	0.20	0.16	0.22	0.15	0.20
	Hardness (mg/L)	16.1	11.1	31.9	22.6	27.9
	Nitrite - Nitrate , as N (mg/L)	<0.05	<0.05	<0.05	<0.05	<0.05
	TKN (mg/L)	0.72	0.16	0.69	0.28	0.25
	Total Phosphorus (mg/L)	0.16	0.15	0.17	0.10	0.16

Table 4-7: Triennial Inorganic Statistics, ASSET Wells

PARAMETER	FY 1995 AVERAGE	FY 1998 AVERAGE	FY 2001 AVERAGE	FY 2004 AVERAGE	FY 2007 AVERAGE
Antimony (ug/L)	<5	-	<5	<5	<1
Arsenic (ug/L)	<5	<5	<5	<5	<3
Barium (ug/L)	62.7	41.4	127.0	85.4	127.9
Beryllium (ug/L)	<2	<2	<2	<1	<1
Cadmium (ug/L)	<2	<2	<2	<1	<0.5
Chromium (ug/L)	<5	<5	<5	<5	<3
Copper (ug/L)	25.1	48.6	7.9	6.6	3.4
Iron (ug/L)	203.1	104.5	160.7	267.4	178.0
Lead (ug/L)	<10	<10	<10	<10	<3
Mercury (ug/L)	<0.05	<0.05	<0.05	<0.05	<0.05
Nickel (ug/L)	8.1	<5	<5	<5	<3
Selenium (ug/L)	<5	<5	<5	<5	<4
Silver (ug/L)	<1	1.19	<1	<1	<0.5
Thallium (ug/L)	<5	<5	<5	<5	<1
Zinc (ug/L)	134.2	106.6	15.2	26.8	15.5

Table 4-8: VOC Analytical Parameters

COMPOUND	METHOD	DETECTION LIMIT (ug/L)
1,1-Dichloroethane	624	2
1,1- Dichloroethene	624	2
1,1,1-Trichloroethane	624	2
1,1,2- Trichloroethane	624	2
1,1,2,2-Tetrachloroethane	624	2
1,2-Dichlorobenzene	624	2
1,2-Dichloroethane	624	2
1,2-Dichloropropane	624	2
1,3- Dichlorobenzene	624	2
1,4-Dichlorobenzene	624	2
Benzene	624	2
Bromoform	624	2
Carbon Tetrachloride	624	2
Chlorobenzene	624	2
Dibromochloromethane	624	2
Chloroethane	624	2
trans-1,2-Dichloroethene	624	2
cis-1,3-Dichloropropene	624	2
Bromodichloromethane	624	2
Methylene Chloride	624	2
Ethyl Benzene	624	2
Bromomethane	624	2
Chloromethane	624	2
o-Xylene	624	2
Styrene	624	2
Methyl-t-Butyl Ether	624	2
Tetrachloroethene	624	2
Toluene	624	2
trans-1,3-Dichloropropene	624	2
Trichloroethene	624	2
Trichlorofluoromethane	624	2
Chloroform	624	2
Vinyl Chloride	624	2
Xylenes, m & p	624	4

Table 4-9: SVOC Analytical Parameters

COMPOUND	METHODS*	DETECTION LIMITS* (ug/L)
1,2-Dichlorobenzene	625/8270	10
1,2,3-Trichlorobenzene	625	10
1,2,3,4-Tetrachlorobenzene	625	10
1,2,4,5-Tetrachlorobenzene	625	10
1,2,4-Trichlorobenzene	625/8270	10
1,3-Dichlorobenzene	625/8270	10
1,3,5-Trichlorobenzene	625	10
1,4-Dichlorobenzene	625/8270	10
2-Chloronaphthalene	625/8270	10
2-Chlorophenol	625/8270	20/10
4,6-Dinitro-2-methylphenol	625/8270	20/10
2-Methylphenol	8270	10
2-Methylnaphthalene	8270	10
2-Nitroaniline	8270	10
2-Nitrophenol	625/8270	20/10
2,4-Dichlorophenol	625/8270	20/10
2,4-Dimethylphenol	625/8270	20/10
2,4-Dinitrophenol	625/8270	20/10
2,4-Dinitrotoluene	625/8270	20/10
2,4,5-Trichlorophenol	8270	10
2,4,6-Trichlorophenol	625/8270	20/10
2,6-Dinitrotoluene	625/8270	10
3,3'-Dichlorobenzidine	625/8270	10
3-Nitroaniline	8270	10
4-Bromophenylphenyl ether	625/8270	10
4-Chloro-3-methylphenol	625/8270	20/10
4-Chloroaniline	8270	10
4-Chlorophenylphenyl ether	625/8270	10
4-Methylphenol	8270	10
4-Nitroaniline	8270	10
4-Nitrophenol	625/8270	20/10
Acenaphthene	625/8270	10
Acenaphthylene	625/8270	10
Anthracene	625/8270	10
Benzo(a)pyrene	625/8270	10
Benzo(k)fluoranthene	625/8270	10
Benzo(a)anthracene	625/8270	10

Table 4-9: SVOCs (Continued)

COMPOUND	METHODS*	DETECTION LIMITS* (ug/L)
Benzo(b)fluoranthene	625/8270	10
Benzo(g,h,i)perylene	625/8270	10
Benzoic acid	8270	10
Benzyl alcohol	8270	10
2,2'-Oxybis(1-chloropropane)	8270	10
Butylbenzylphthalate	625/8270	10
Chrysene	625/8270	10
Dibenz(a,h)anthracene	625/8270	10
Dibenzofuran	8270	10
Diethylphthalate	625/8270	10
Dimethylphthalate	625/8270	10
Di-n-butylphthalate	625/8270	10
Di-n-octylphthalate	625/8270	10
Fluoranthene	625/8270	10
Fluorene	625/8270	10
Hexachlorobenzene	625/8270	10/1
Hexachloro-1,3-butadiene	8270	10
Hexachlorocyclopentadiene	625/8270	10
Hexachloroethane	625/8270	10
Indeno(1,2,3-cd)pyrene	625/8270	10
Isophorone	625/8270	10
Naphthalene	625/8270	10
Nitrobenzene	625/8270	10
N-Nitrosodimethylamine	625	10
N-Nitrosodiphenylamine	625/8270	10
N-Nitroso-di-n-propylamine	625/8270	10
Pentachlorophenol	625/8270	10/1
Pentachlorophenol	625	20
Phenanthrene	625/8270	10
Phenol	625/8270	20/10
Pyrene	625/8270	10

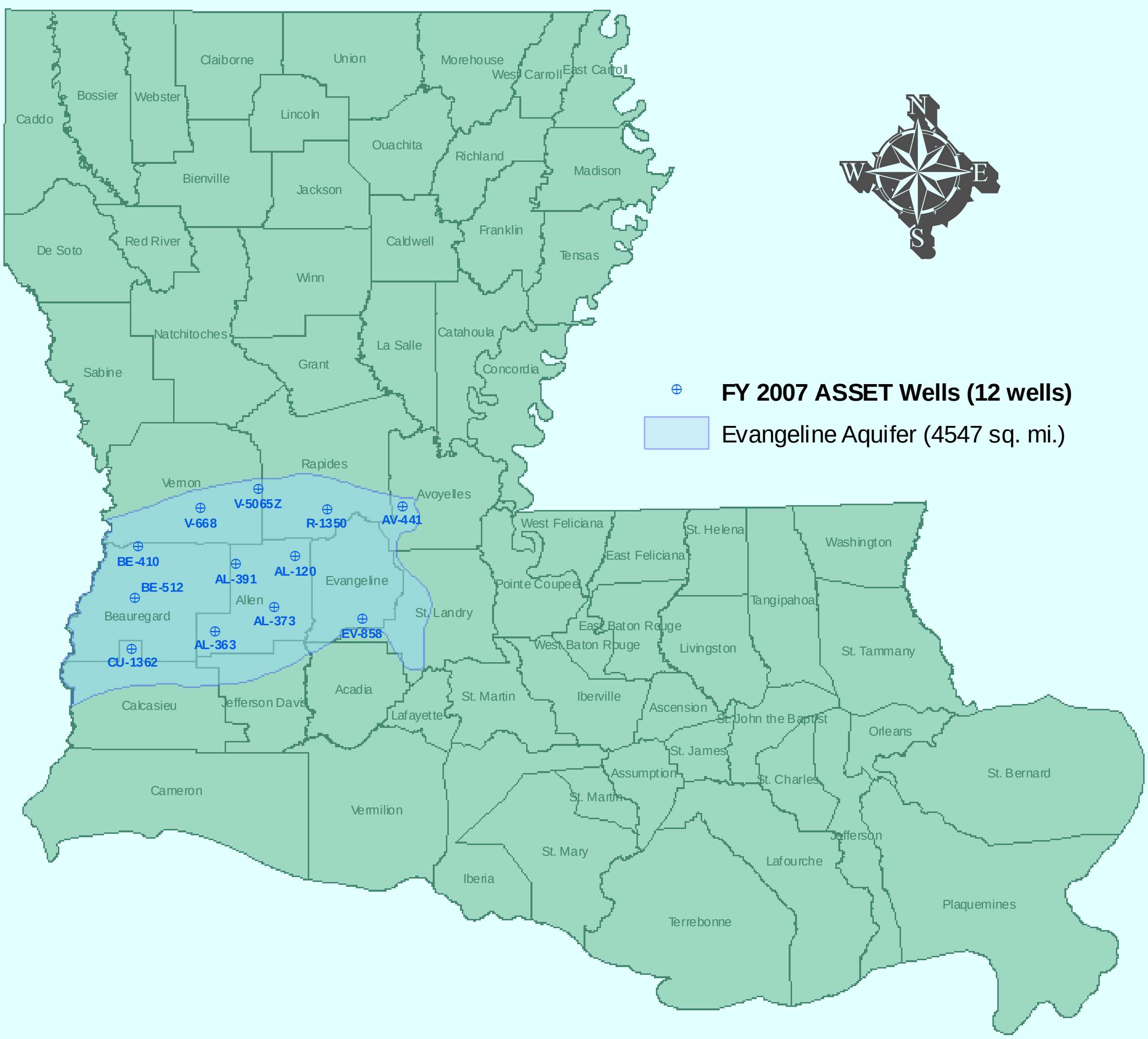
*Multiple methods/detection limits due to multiple labs performing analyses.

Table 4-10: Pesticides and PCBs

COMPOUND	METHODS*	DETECTION LIMITS* (ug/L)
4,4'-DDD	608 / 8081	0.05 / 0.1
4,4'-DDE	608 / 8081	0.05 / 0.1
4,4'-DDT	608 / 8081	0.05 / 0.1
Aldrin	608 / 8081	0.05 / 0.05
alpha-Chlordane	608 / 8081	0.05 / 0.05
alpha-BHC	608 / 8081	0.05 / 0.05
beta-BHC	608 / 8081	0.05 / 0.05
delta-BHC	608 / 8081	0.05 / 0.05
gamma-BHC	608 / 8081	0.05 / 0.05
Chlordane	608	0.2
Dieldrin	608 / 8081	0.05 / 0.1
Endosulfan I	608 / 8081	0.05 / 0.05
Endosulfan II	608 / 8081	0.05 / 0.1
Endosulfan sulfate	608 / 8081	0.05 / 0.1
Endrin	608 / 8081	0.05 / 0.1
Endrin aldehyde	608 / 8081	0.05 / 0.1
Endrin Ketone	608 / 8081	0.05 / 0.1
Heptachlor	608 / 8081	0.05 / 0.05
Heptachlor epoxide	608 / 8081	0.05 / 0.05
Methoxychlor	608 / 8081	0.05 / 0.5
Toxaphene	608 / 8081	2 / 2
gamma- Chlordane	608 / 8081	0.05 / 0.05
Aroclor 1016	608 / 8081	1 / 1
Aroclor 1221	608 / 8081	1 / 1
Aroclor 1232	608 / 8081	1 / 1
Aroclor 1242	608 / 8081	1 / 1
Aroclor 1248	608 / 8081	1 / 1
Aroclor 1254	608 / 8081	1 / 1
Aroclor 1260	608 / 8081	1 / 1

*Multiple methods/detection limits due to multiple labs performing analyses.

Figure 4-1: Location Plat, Evangeline Aquifer



Aquifer Boundary digitized from Louisiana Hydrologic Map No. 2: Areal Extent of Freshwater In Major Aquifers of Louisiana, Smoot, 1986; USGS/LDOTD Report 86-4150.

ASSET PROGRAM, FY 2007

Figure 4-2: Map of pH Data

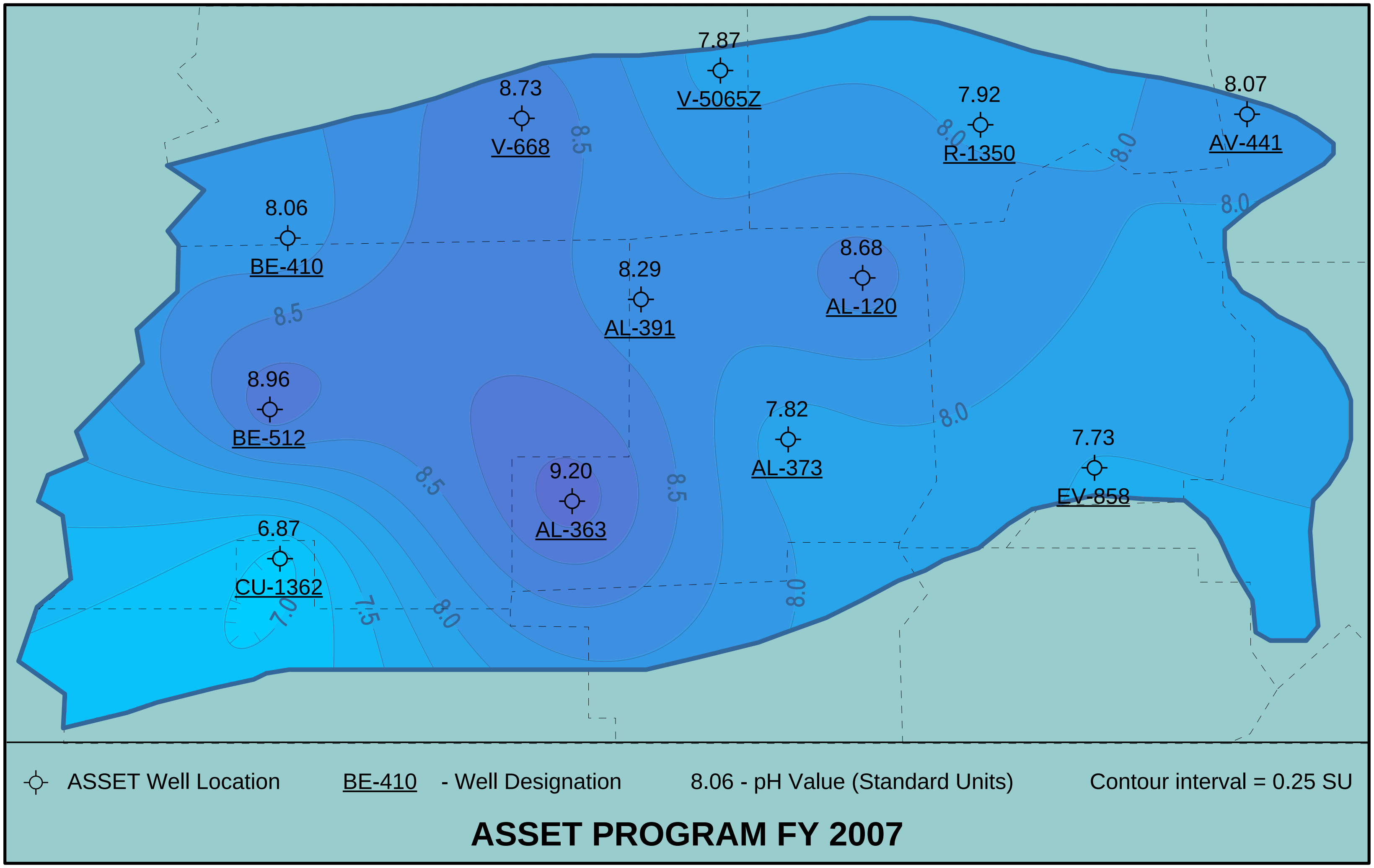


Figure 4-3: Map of TDS Lab Data

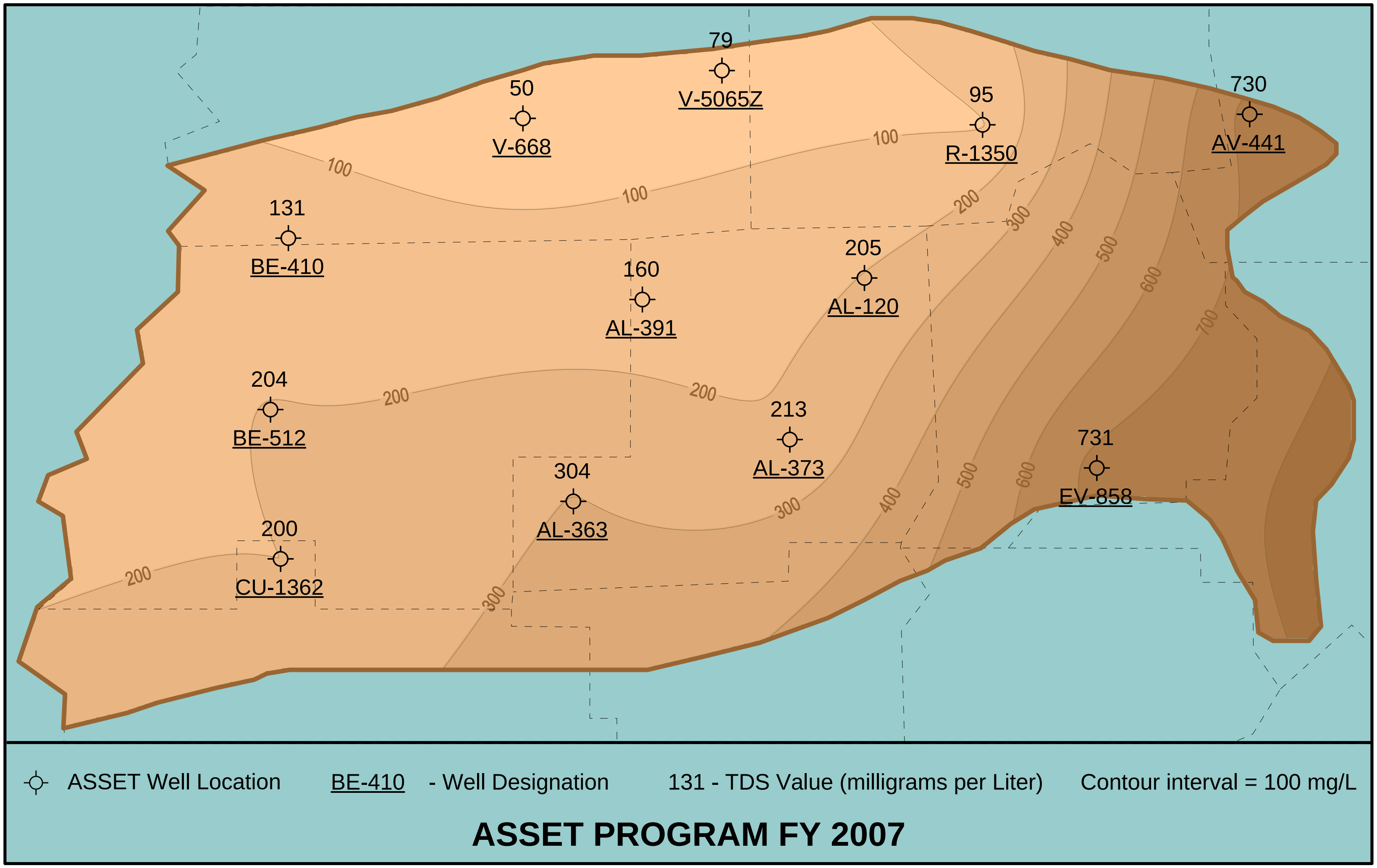


Figure 4-4: Map of Chloride Data

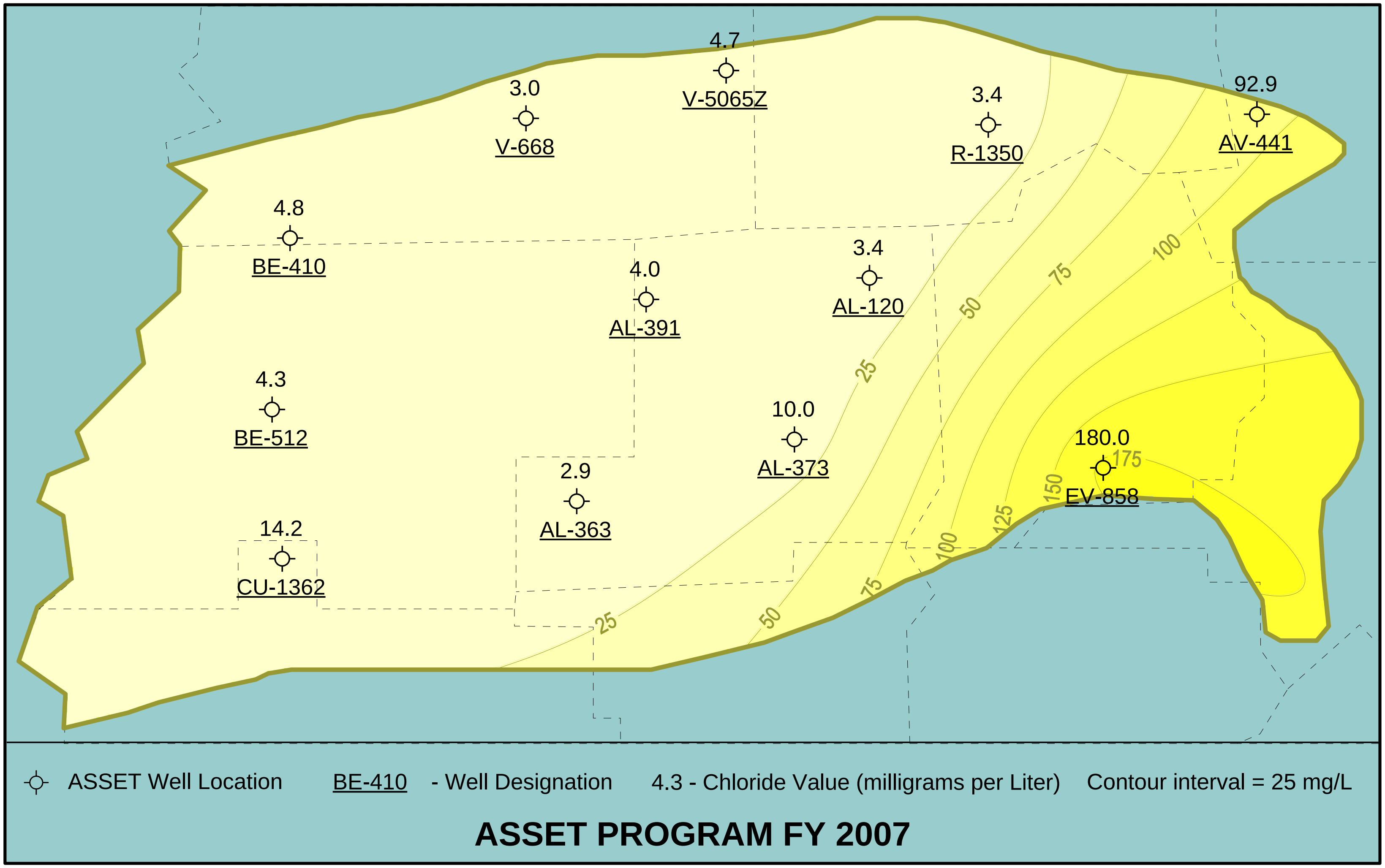


Figure 4-5: Map of Iron Data

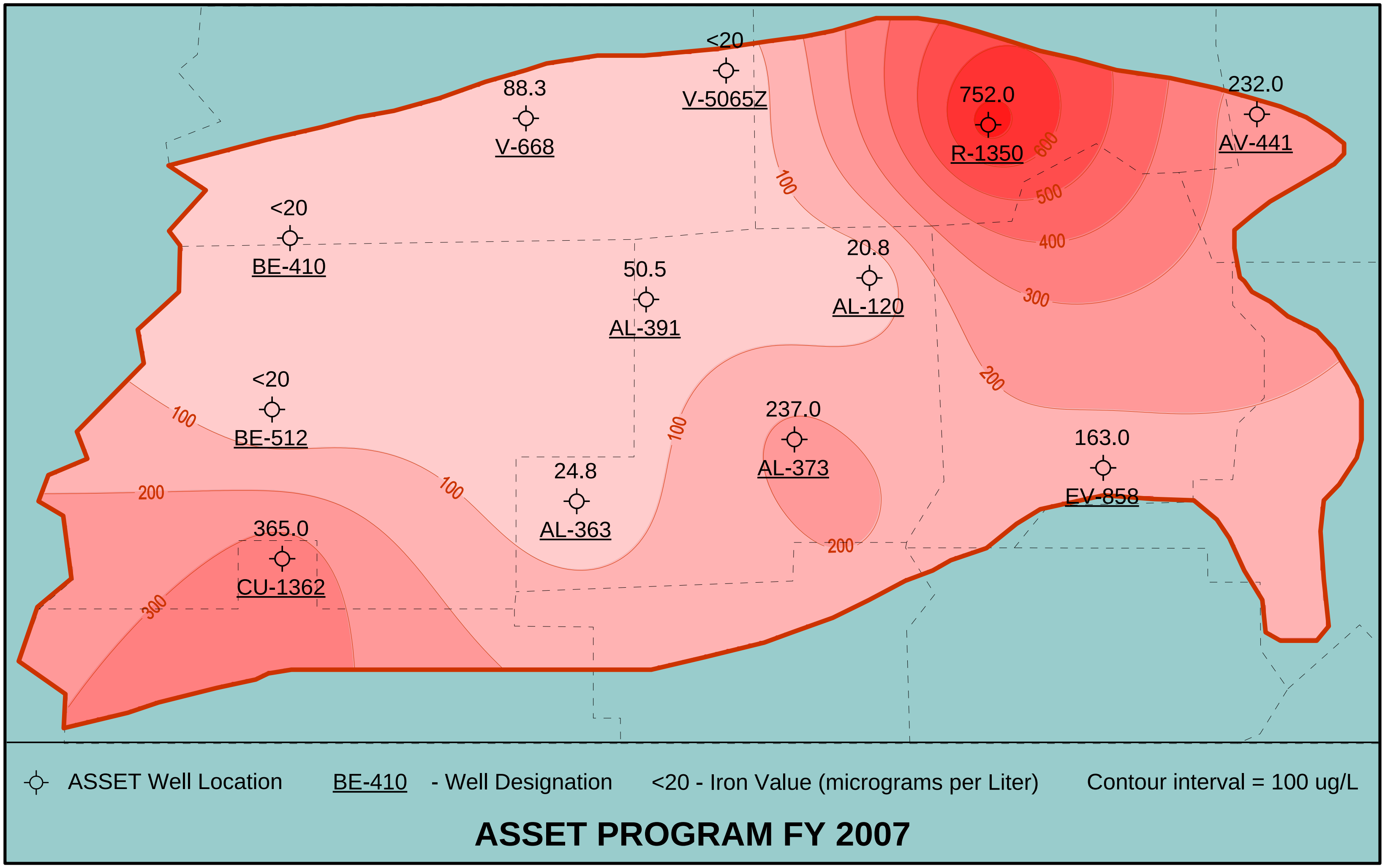


Chart 4-1: Temperature Trend

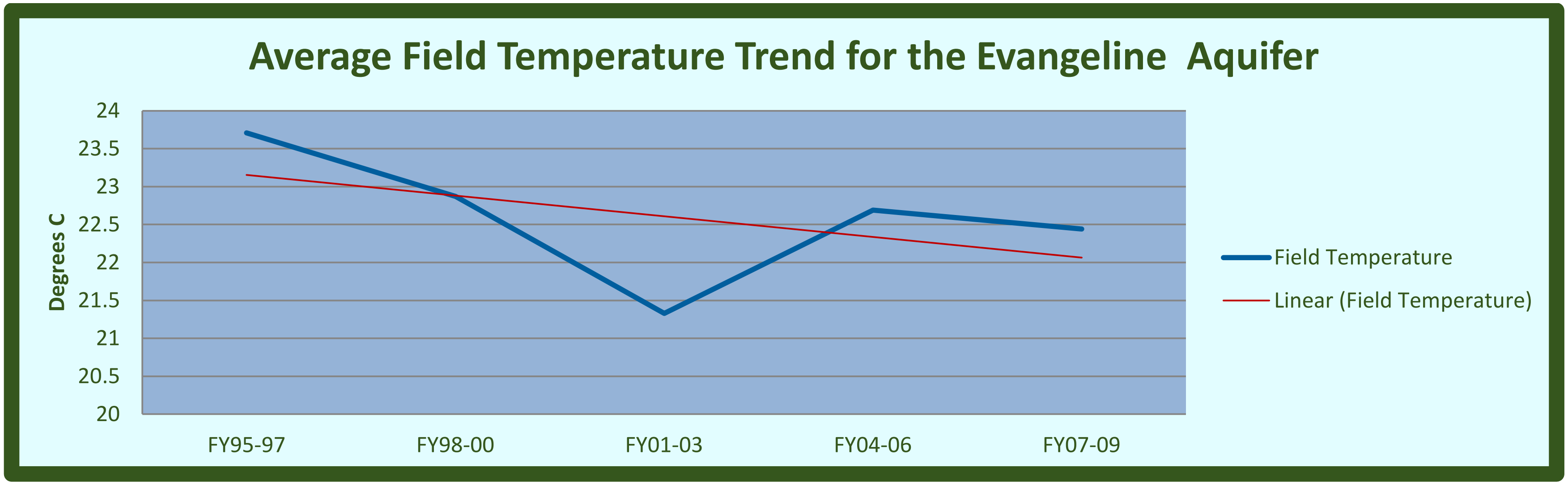


Chart 4-2: pH Trend

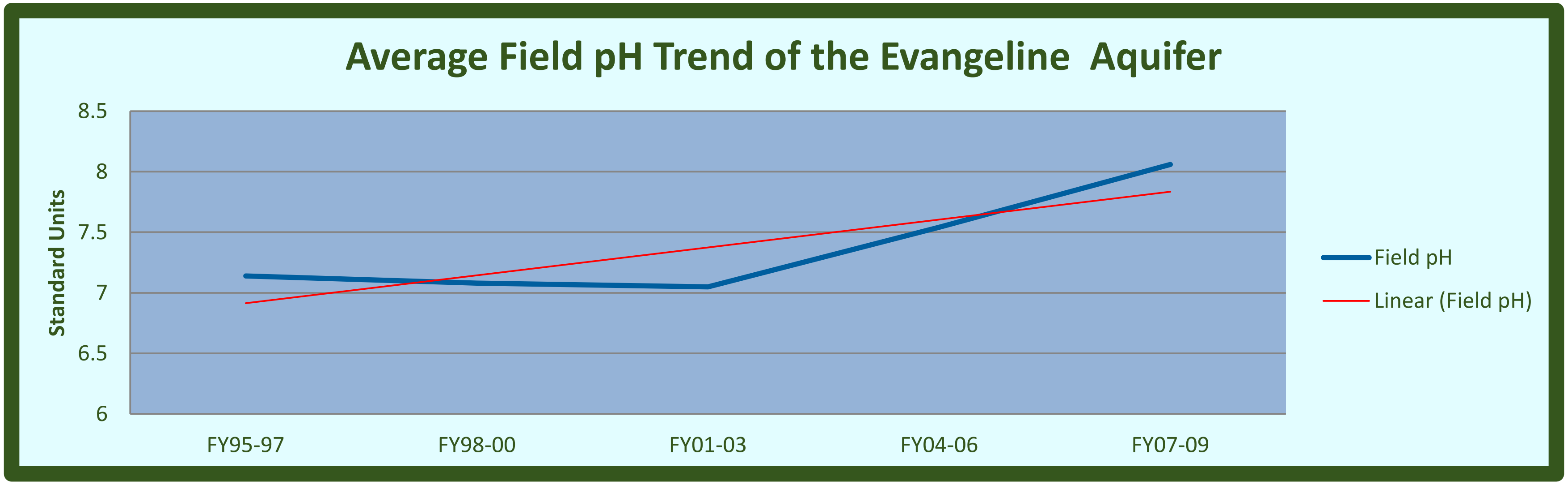


Chart 4-3: Field Specific Conductance Trend

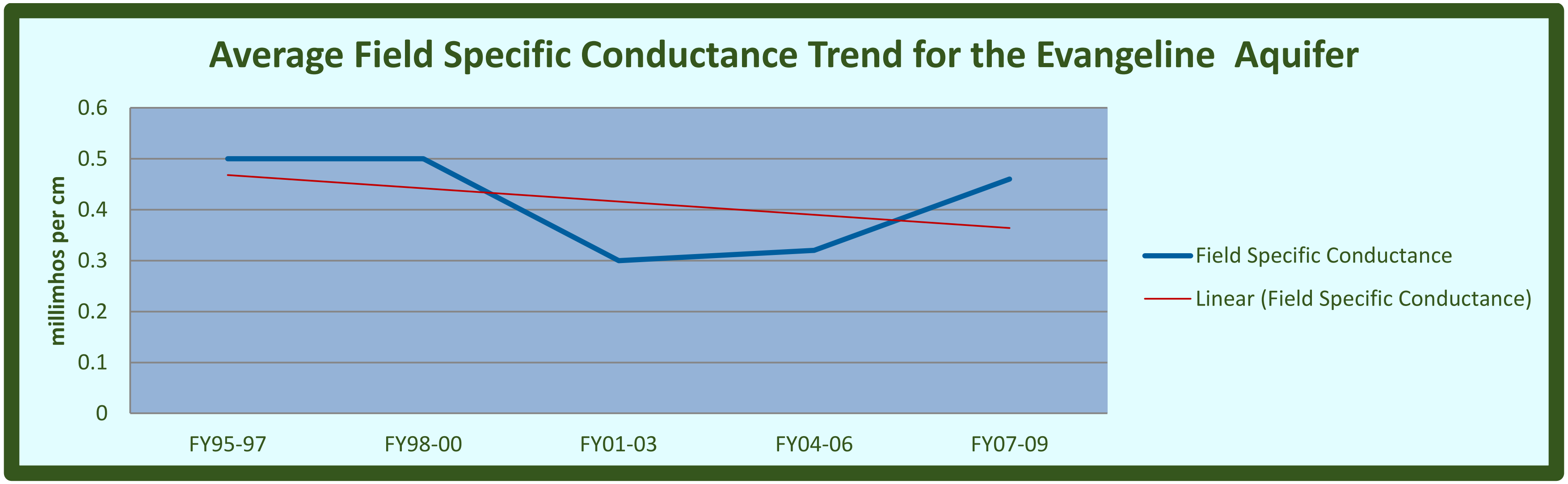


Chart 4-4: Lab Specific Conductance Trend

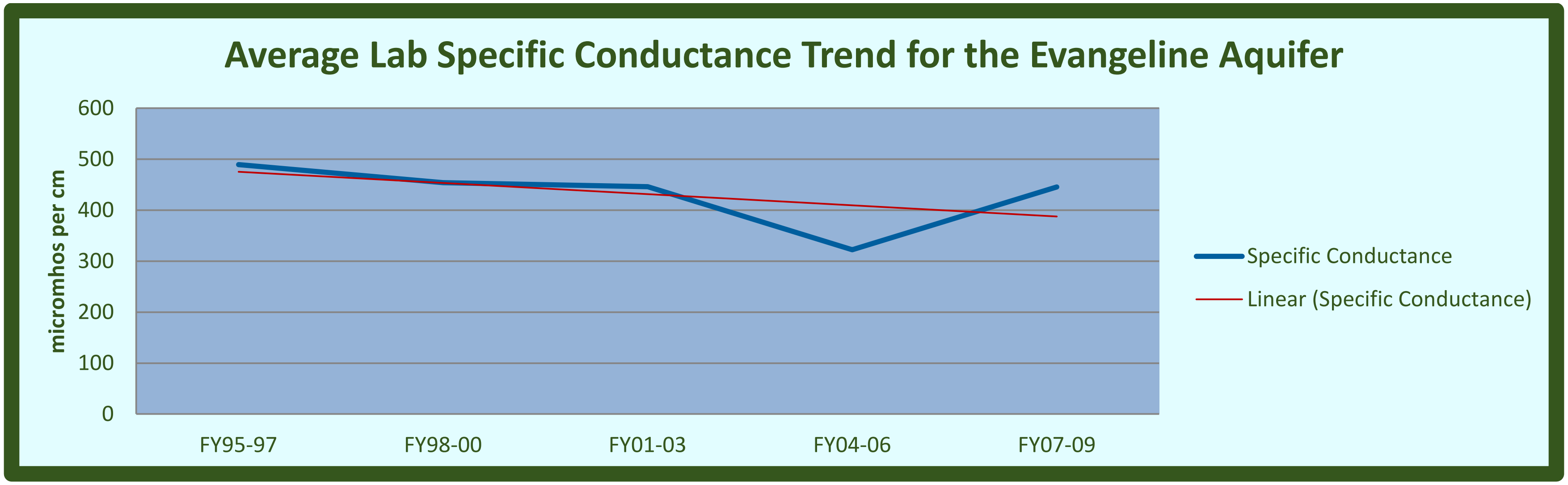


Chart 4-5: Field Salinity Trend

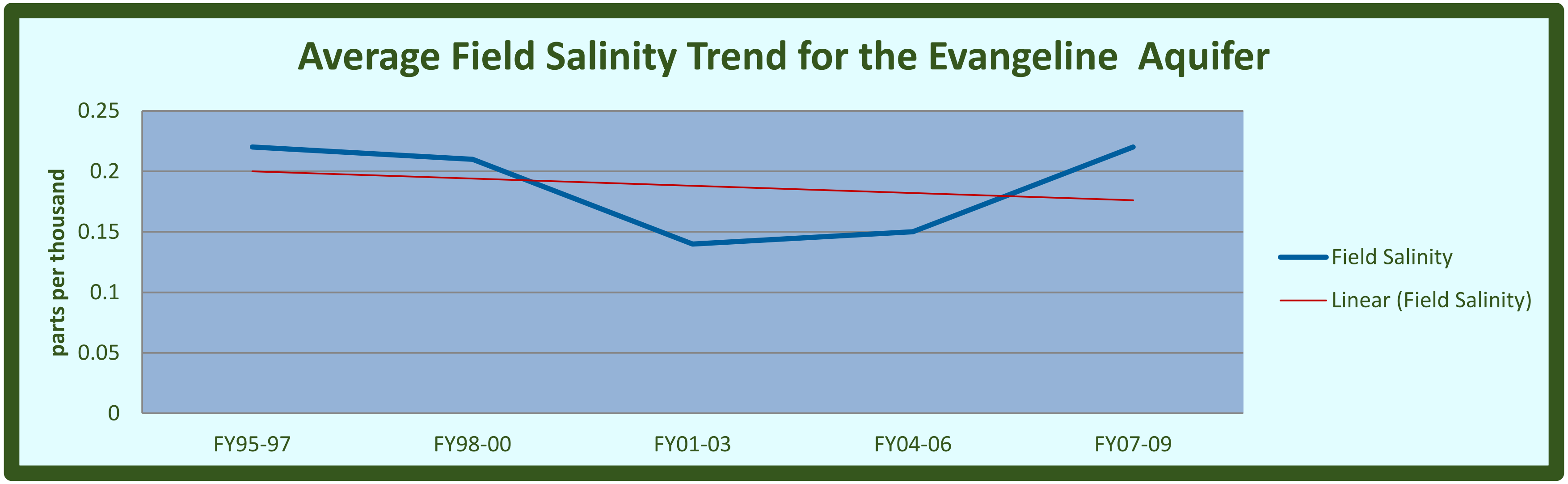


Chart 4-6: Alkalinity Trend

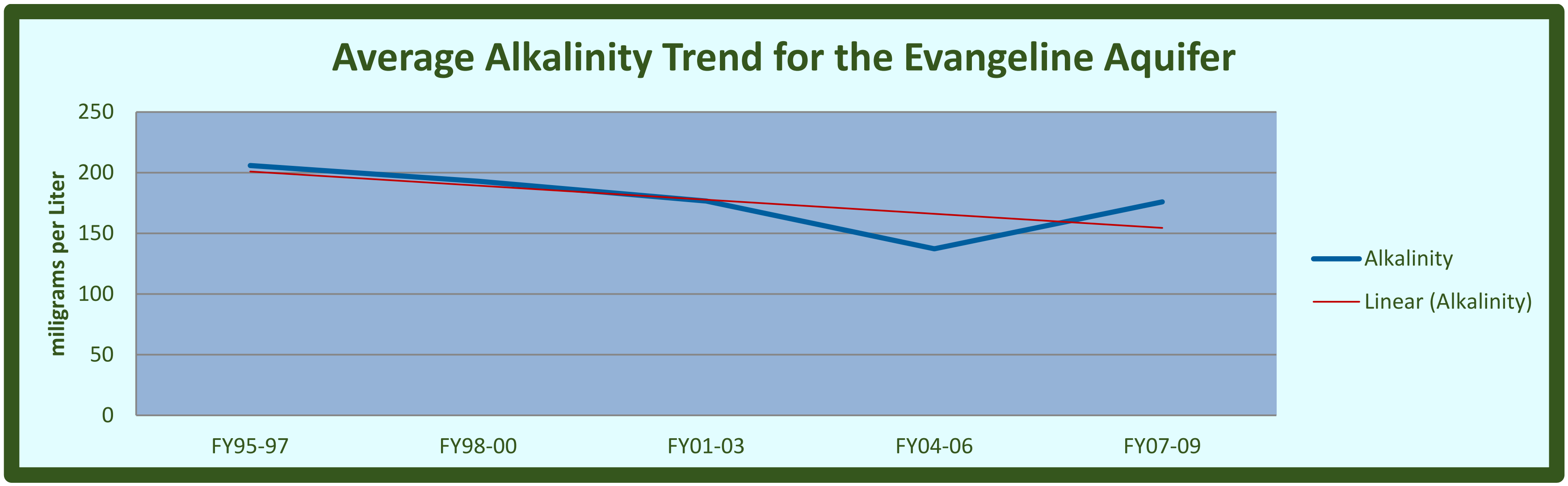


Chart 4-7: Chloride Trend

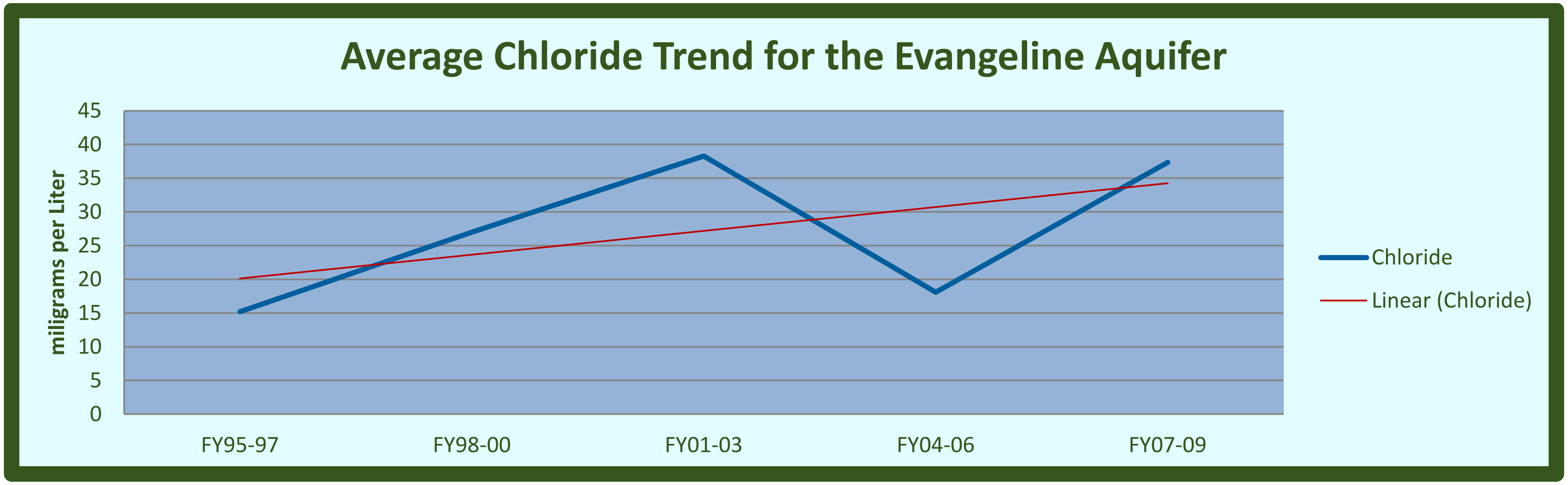


Chart 4-8: Color Trend

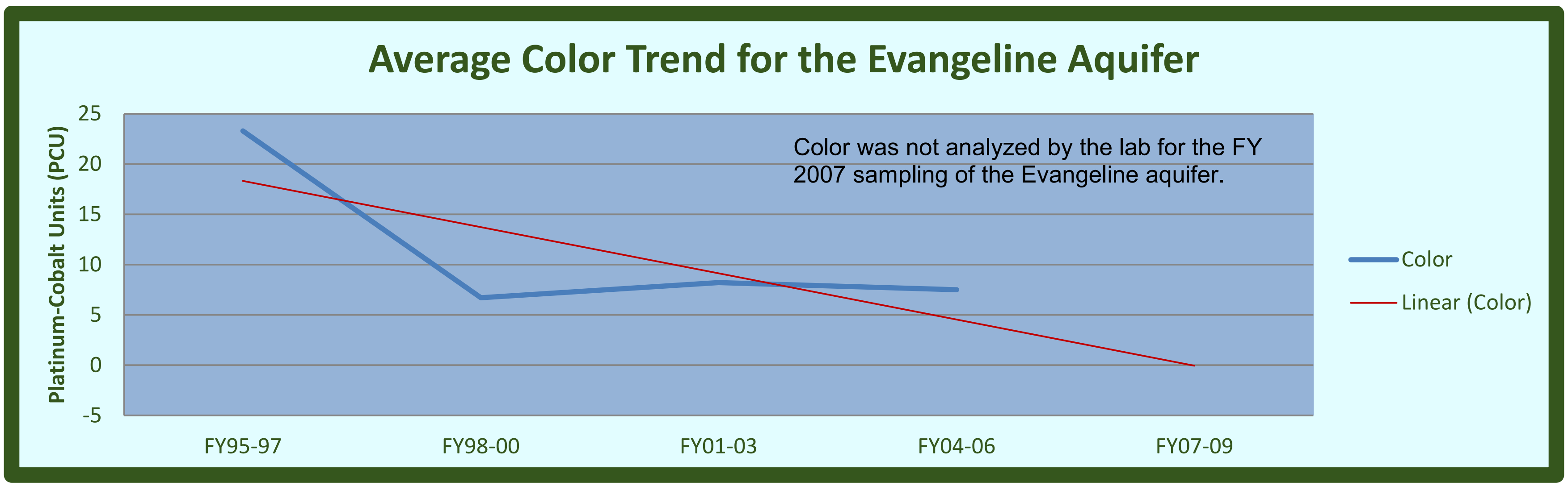


Chart 4-9: Sulfate (SO4) Trend

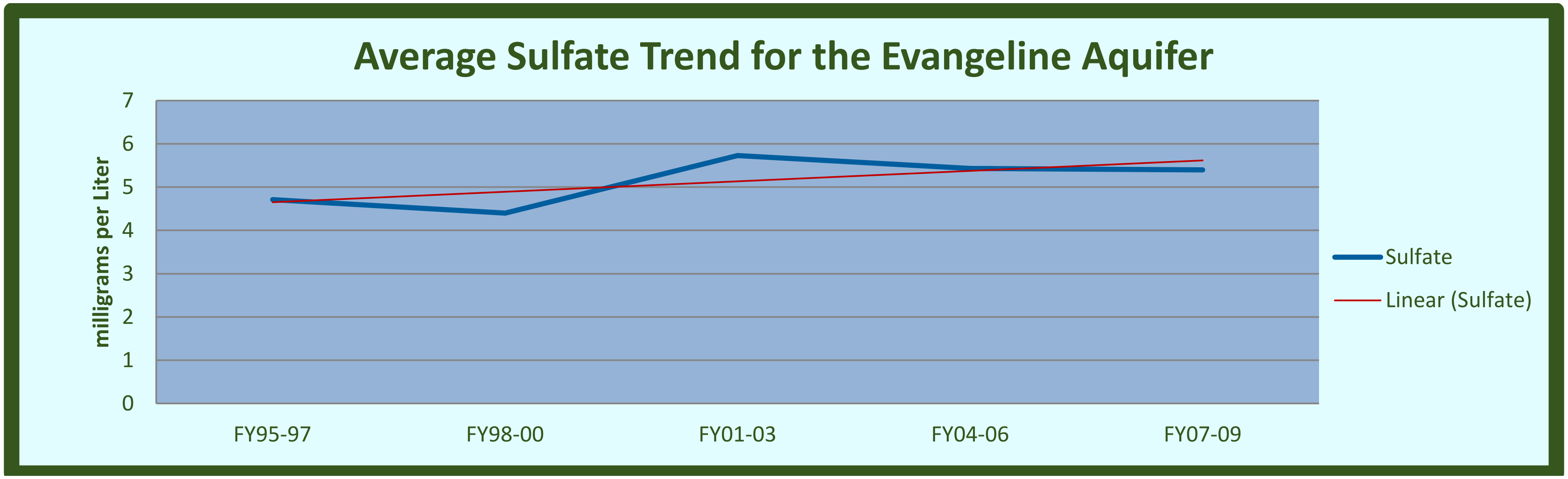


Chart 4-10: Total Dissolved Solids (TDS) Trend

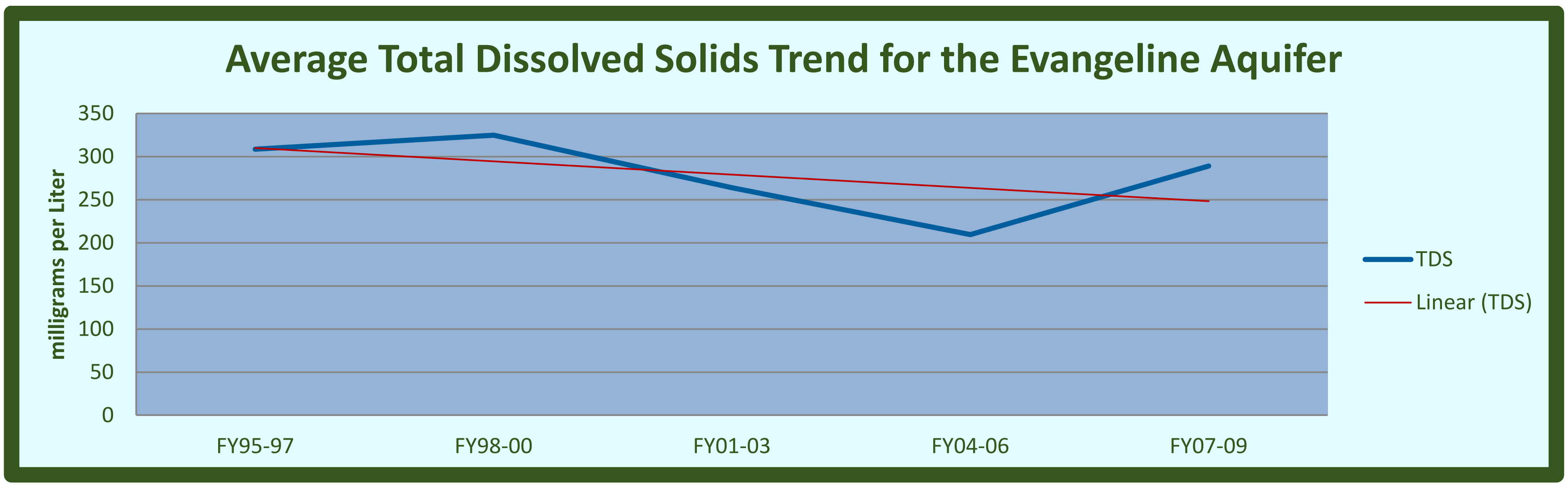


Chart 4-11: Ammonia (NH4) Trend

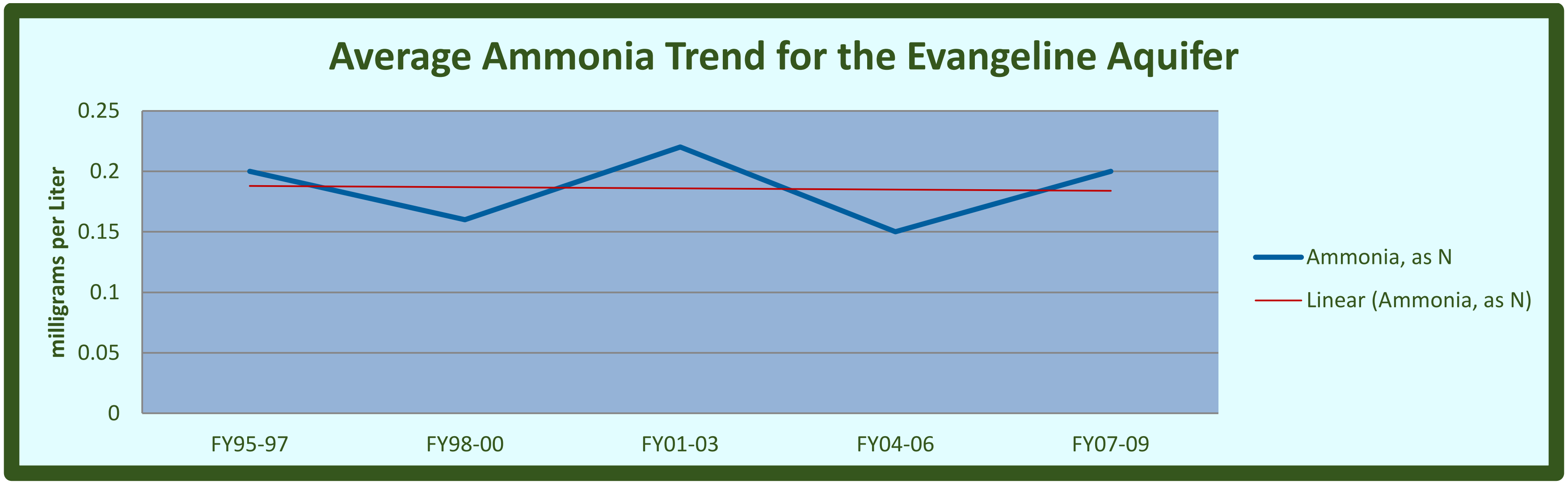


Chart 4-12: Hardness Trend

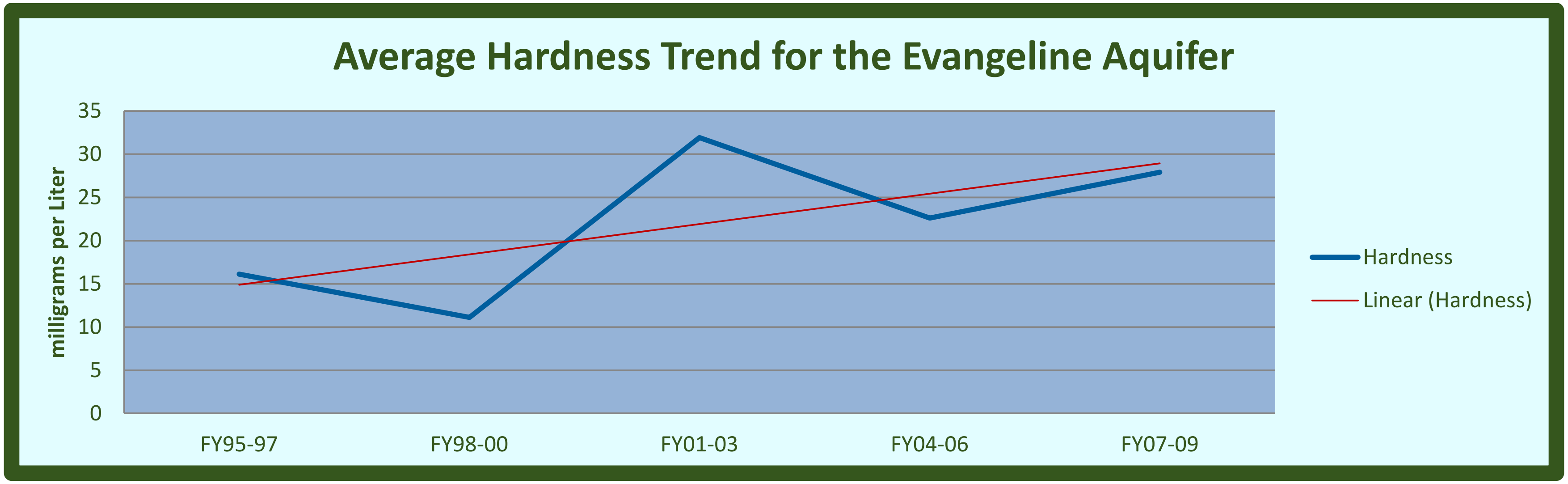


Chart 4-13: Nitrite – Nitrate Trend

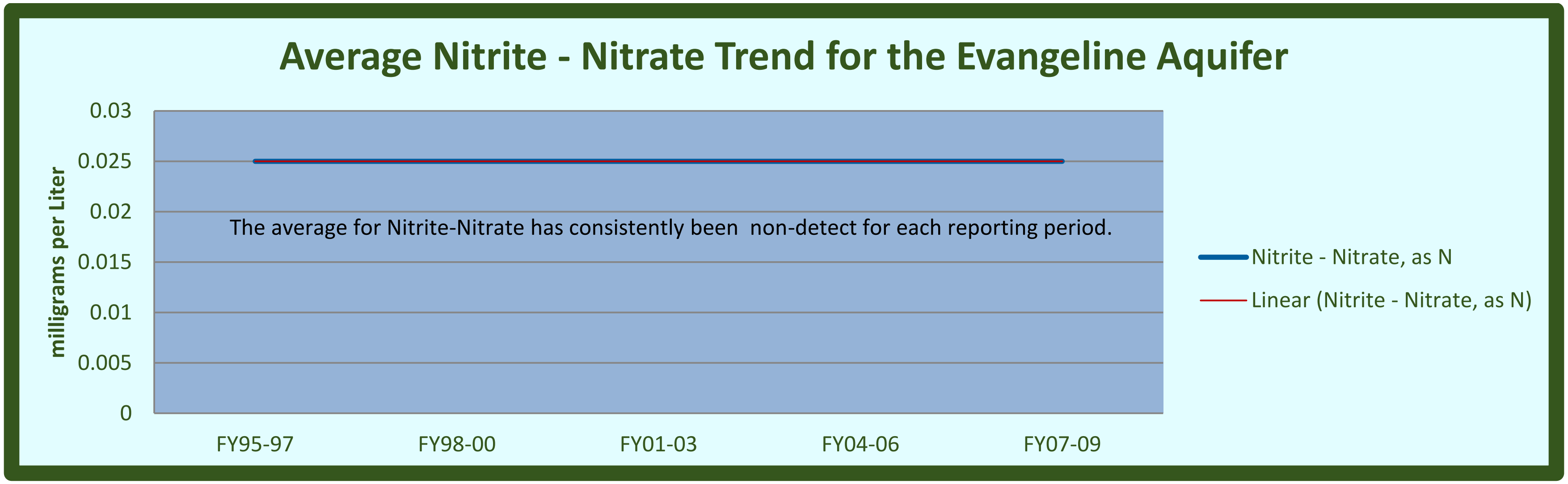


Chart 4-14: TKN Trend

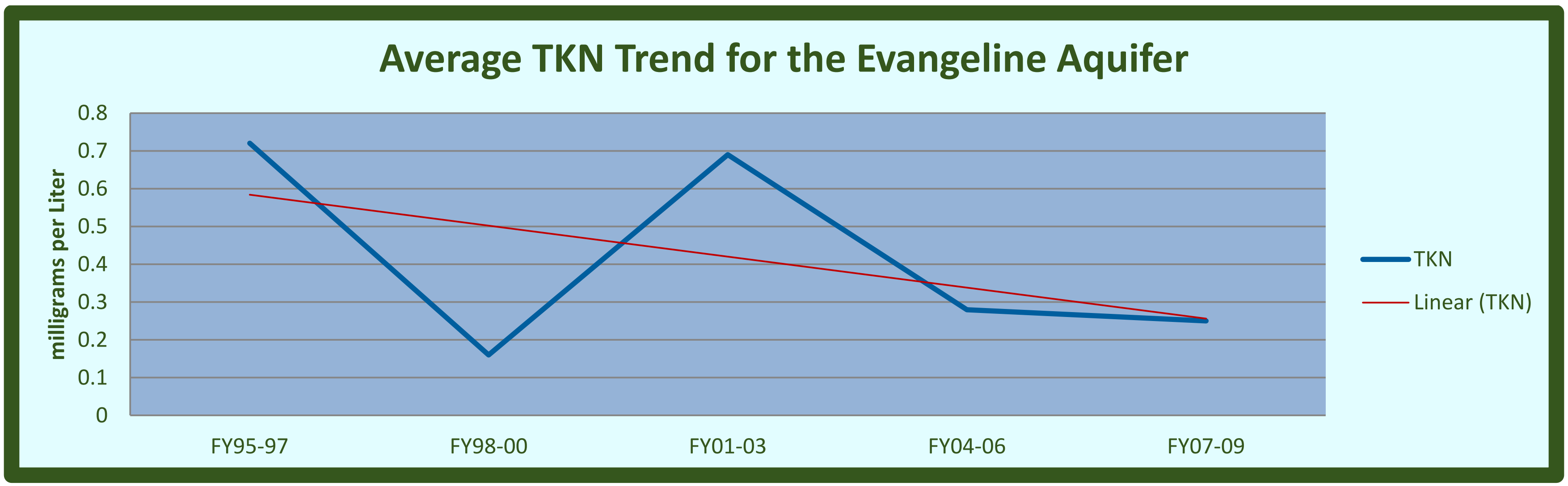


Chart 4-15: Total Phosphorus Trend

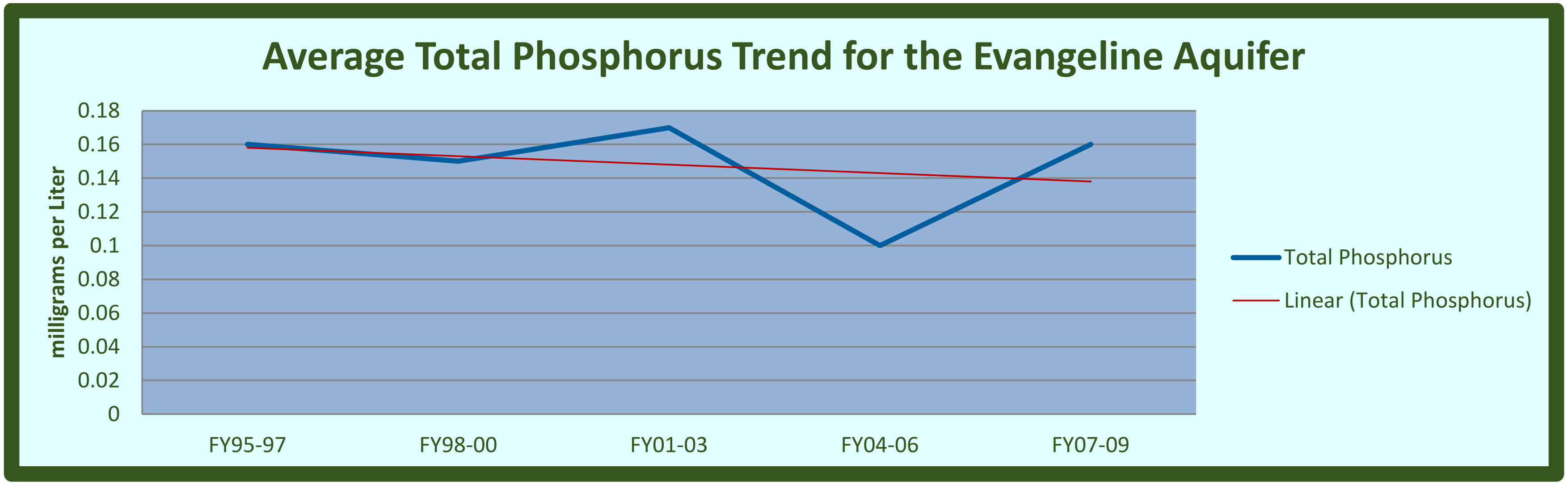
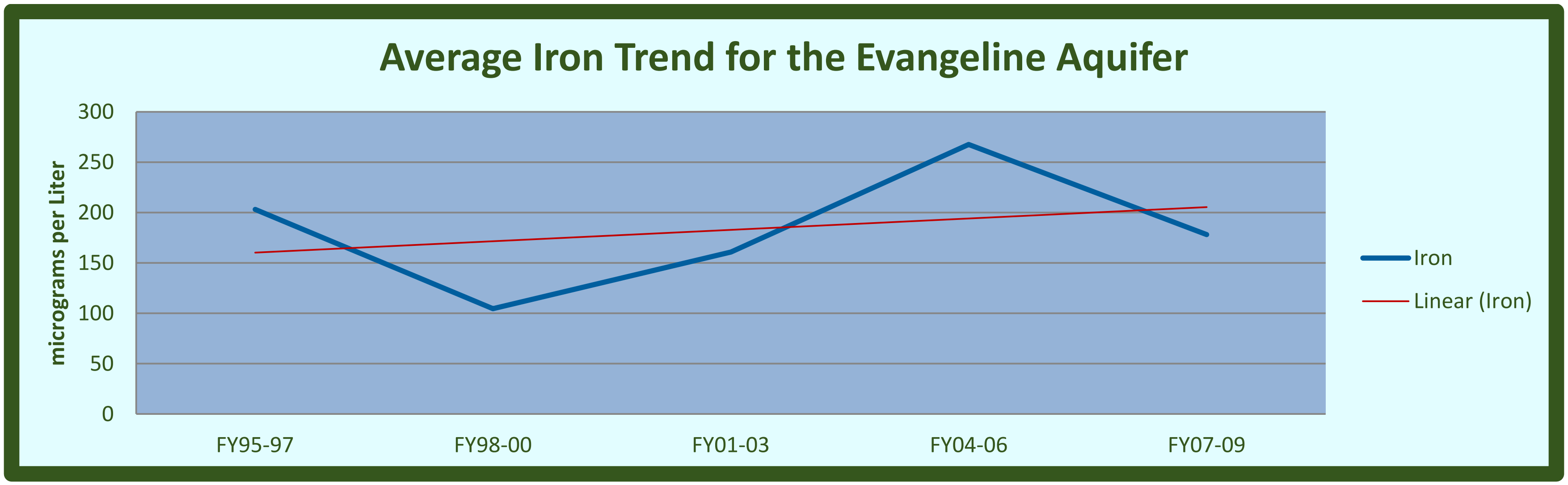


Chart 4-16: Iron Trend



HARDER, A.H., 1960

THE GEOLOGY AND GROUNDWATER RESOURCES OF CALCASIEU PARISH, LOUISIANA

The Geology and Ground-Water Resources of Calcasieu Parish Louisiana

By ALFRED H. HARDER

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1488

Prepared in cooperation with the Louisiana Department of Public Works and the Louisiana Geological Survey, Department of Conservation

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1960

UNITED STATES DEPARTMENT OF THE INTERIOR

FRED A. SEATON, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington 25, D.C.

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THE GEOLOGY AND GROUND-WATER RESOURCES OF CALCASIEU PARISH, LOUISIANA

By A. H. Harder

ABSTRACT

Large quantities of fresh ground water are available in Calcasieu Parish. Fresh water is present in sand of Recent, Pleistocene, Pliocene, and Miocene ages, although locally only small supplies for rural or stock use can be obtained from the shallow sand lenses of Recent and Pleistocene ages. The principal fresh-water-bearing sands are the "200-foot," "500-foot," and "700-foot" sands of the Chicot aquifer of Pleistocene age, from which 105 million gallons is pumped daily. A yield of as much as 4,500 gpm (gallons per minute) has been obtained from a single well. The sands are typical of the Chicot aquifer throughout southwestern Louisiana in that generally they grade from fine sand at the top to coarse sand and gravel at the base of the aquifer.

The coefficient of permeability of the principal sands in Calcasieu Parish ranges from 660 to about 2,000 gpd (gallons per day) per square foot and averages 1,200 gpd per square foot. The permeability of the sands generally varies with textural changes.

The maximum depth of occurrence of fresh ground water in Calcasieu Parish ranges from about 700 feet to 2,500 feet below mean sea level; locally, however, where the sands overlie structures associated with oil fields, the maximum depth is less than 300 feet.

Pumping has caused water levels to decline, at varying rates, in all the sands. In the "200-foot" sand they are declining at a rate of about 2 feet per year. In the industrial district of Calcasieu Parish, levels in the "500-foot" sand are declining at a rate of about 5 feet per year, and in the "700-foot" sand at a rate of about 3.5 feet per year. Salt-water contamination is accompanying the water-level decline in the "700-foot" sand in the central part of the parish.

Quality-of-water data indicate that water from wells screened in the Chicot aquifer generally is suitable for some uses without treatment but would require treatment to be satisfactory for other uses. The temperature of the water ranges from 70° to 79°F.

The lenticular sands of Pliocene and Miocene ages have not been used as a source of fresh ground water in Calcasieu Parish; however, north of the Houston River these formations contain fresh water, and the water contained in these formations in other parts of southwestern Louisiana is known to be soft and suitable for most purposes.

INTRODUCTION

LOCATION AND GENERAL FEATURES OF THE AREA

Calcasieu Parish is in southwestern Louisiana (fig. 1) and is bordered on the west by the Sabine River and on the north, east, and south by Beauregard, Jefferson Davis, and Cameron Parishes, respectively. It has an area of 1,070 square miles, an extreme east-west length of about 50 miles, and an extreme north-south length of about 30 miles. In this report the Lake Charles industrial district is considered to be the area along the west side of the Calcasieu River between Moss Lake and the city of Lake Charles. In Calcasieu Parish there are 24 producing oil or gas fields and 1 sulfur mine which, with the refineries and chemical plants in the industrial district near Lake Charles, make the parish an important petroleum and chemical center. At DeQuincy, turpentine and other related products are produced. The principal agricultural products in the parish are rice, lumber, and cattle.

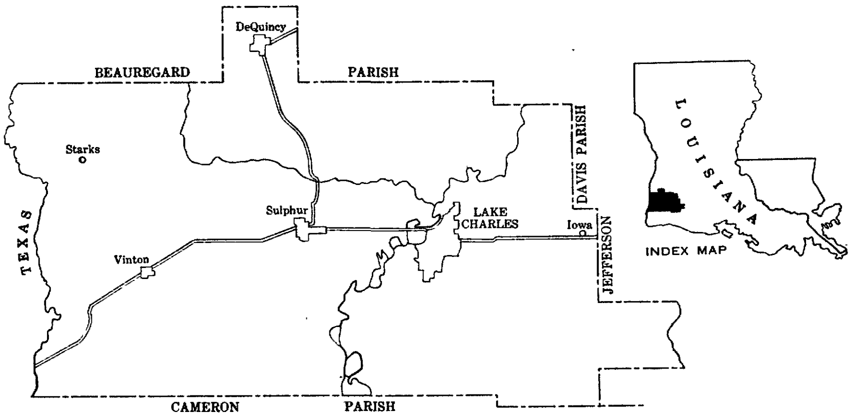

FIGURE 1.—Index map of Calcasieu Parish.

According to the 1950 census the population of the parish was 89,635. The principal city is Lake Charles, a deepwater port on the Calcasieu River. The population of Lake Charles in 1940 was 21,207 and by 1950 had increased 94 percent to 41,272. In addition to the large chemical plants and refineries in the industrial district, there are many small industries across the Calcasieu River in Lake Charles. McNeese State College is in Lake Charles, and the Lake Charles Air Force Base is just outside the city limits.

The city is serviced by the Southern Pacific, the Kansas City Southern, and the Missouri Pacific Railroads; by the Greyhound and Continental Trailways bus lines; and by Trans-Texas Airways and Eastern Air Lines. A deepwater ship channel, first completed in 1941 and subsequently deepened to 35 feet, connects Lake Charles with the Intracoastal Waterway and the Gulf of Mexico by a route that approximates the natural channel of the Calcasieu River.

PURPOSE AND SCOPE OF THE INVESTIGATION

The aquifers underlying Calcasieu Parish provide an important source of water for industrial, municipal, irrigation, and rural use. Water from rivers, lakes, and canals also is used for irrigation and industrial purposes; however, because of the varying temperatures and often poor quality of the surface water, industries and irrigators use large quantities of ground water. In 1955 about 23.7 billion gallons of ground water was pumped by industries, about 9.90 billion gallons for irrigation, about 2.86 billion gallons for municipal supplies, and about 1.46 billion gallons for rural supplies.

It is difficult to determine the dollar value of ground water, because it is used for many different purposes. However, if this source of water, as developed by the industries in Calcasieu Parish, were depleted and had to be replaced by another source at the relatively low industrial rate of 8 cents per thousand gallons, the annual cost of the water used for industrial purposes would be about $1.9 million.

Because of the expanding industrial and municipal use of ground water and its widespread use for irrigation and rural needs, concern has been expressed about the adequacy of ground-water supplies throughout the parish. Because of the seriousness of salt-water encroachment in the Calcasieu River at Lake Charles (Jones and others, 1956, p. 186), future municipal, agricultural, and industrial developments along the river will be dependent primarily upon wells for an adequate fresh-water supply.

Basic information on ground-water conditions has been collected since 1941. In 1954 a detailed ground-water study of the parish was begun to present the pertinent basic data thus far collected, determine the availability of ground water as indicated by the geologic conditions and the hydrologic properties of the aquifers, determine the occurrence of fresh ground water and its chemical quality, and determine the rates of withdrawals and their effects. This study was made in cooperation with the Louisiana Geological Survey, Department of Conservation, and the Louisiana Department of Public Works. The work was done under the immediate supervision of Rex R. Meyer, district geologist of the Ground Water Branch, United States Geological Survey.

About 670 wells have been inventoried in the parish; records of some of these wells are given in table 6 and their locations are shown on plates 1 and 2. Water-level fluctuations in the principal aquifers were measured in selected wells to determine changes in storage and effects of pumping. Drillers' logs, electrical logs, and pumping tests were the principal bases for determining the extent of the fresh-water-bearing sands. The ability of the aquifers to store and transmit water was determined by means of pumping tests. Water samples were obtained and analysed to determine the chemical constituents in the water and to outline areas yielding water of high salinity. The amount of water pumped in the area was computed from reports by users, from the rating of individual wells used to irrigate rice, and from estimates of rural use based on population. The maximum depth of occurrence of fresh ground water and the presence of deep aquifers in northern and central Calcasieu Parish were determined chiefly from electrical logs of oil-test wells.

PREVIOUS INVESTIGATIONS

Harris and Veatch (1905) were the first to report water levels, chemical analyses, and logs of wells in Calcasieu Parish. Jones (1950) described the occurrence of ground water in the vicinity of Lake Charles. He also named the "200-," "500-," and "700-foot" sands and determined the withdrawals and their effect on water levels. Coefficients of transmissibility and storage and data on the quality of water in the three sands also were presented. Jones, Turcan, and Skitbitske (1954) described the ground-water conditions in Calcasieu Parish in detail in their report on southwestern Louisiana. A more recent paper (Jones and others, 1956) on the same area incorporates the earlier report. Piezometric maps of the principal aquifer in southwestern Louisiana for the period 1952–55 are included in three reports published jointly by the Louisiana Geological Survey and the Louisiana Department of Public Works (Fader, 1954, 1955, and 1957).

ACKNOWLEDGMENTS

The author thanks the many people whose excellent cooperation made this report possible. Information on well construction, water consumption, and water quality was made readily available by individual well owners and by the Cit-Con Oil Corp., Cities Services Refining Corp., Columbia-Southern Chemical Corp., Continental Oil Co., Davison Chemical Co., Firestone Tire and Rubber Co., Greater Lake Charles Water Co., Gulf States Utilities Co., Newport Industries, Inc., Olin Mathieson Chemical Corp., and Petroleum Chemicals, Inc. Irrigation well owners and industrial officials were very helpful in making wells available for pumping tests. The Coastal Water Well Corp., Layne Louisiana Co., Stamm-Scheele, Inc., and other water-well contractors provided well-construction data and

drillers' logs. Considerable subsurface information was obtained from electrical logs of oil-test wells made available by Leo W. Hough, State geologist, Louisiana Department of Conservation. Many thanks also are due various State and Federal agencies, the Louisiana Department of Public Works, the Louisiana Department of Highways, the U.S. Corps of Engineers, the U.S. Air Force, and the U.S. Weather Bureau Station at the Lake Charles Air Force Base for pertinent data supplied by them. The Louisiana State Rice Milling Co. and the U.S. Department of Agriculture provided rice-acreage and water-source data.

WELL-NUMBERING SYSTEM

All wells inventoried by the U.S. Geological Survey in Calcasieu Parish are designated by the prefix "Cu," a symbol for the parish, followed by a number denoting a specific well in the parish. Where possible, all wells are located to the closest 16th section within the proper township and range. A record of each well is kept on file, and the well's location is plotted on a map. Data on wells pertinent to this report are given in table 6, and the well locations are shown on plates 1 and 2.

LANDFORMS AND DRAINAGE

Calcasieu Parish lies in the West Gulf Coastal Plain (Fenneman, 1938, p. 102). It is an area of low relief—the altitude ranges from about 2 feet on the flood plains of the Sabine and Calcasieu Rivers to about 90 feet in the area northwest of DeQuincy. North of the Houston River the land is somewhat hilly, and altitudes range from about 20 to 90 feet, whereas south of the Houston the land is a very flat plain whose altitude ranges from 25 feet near the river to about 2 feet in the coastal marsh. The minimum slope of the coastwise Pleistocene terrace is about 2 feet per mile, whereas the slope of the Recent flood plains generally is less than, and is dependent upon, the gradient of the streams which formed them. Meander scars, representing courses of ancestral streams, and pimple mounds are present on the Pleistocene surface throughout the parish. The pimple mounds are low circular or elliptical hillocks, generally 30 to 50 feet in diameter and about 1 to 5 feet in height (Jones and others, 1956, p. 25). Within the past 10 years farmers have made considerable use of land-leveling machinery to smooth out these irregularities because of their hindrance to irrigation and planting.

The flood plains are usually swampy in comparison to the surrounding uplands; consequently, the plant growth on the flood plains is quite different from that on the better drained Pleistocene surfaces. The flood plains contain such trees as oak, gum, and magnolia, and a very dense undergrowth, whereas the Pleistocene surface not under cultivation contains grassland and pine trees.

The parish is drained by the Calcasieu and Sabine Rivers and their tributaries. One of the largest tributaries of the Calcasieu River is the Houston River, which, with its tributaries, drains most of the northwestern part of the parish.

CLIMATE

The climate of Calcasieu Parish is mild and is typically that of the Gulf Coast States. The average annual temperature for the period 1900–55 was 68°F. The highest temperature recorded during this period was 104°F in August 1951, and the lowest was 12°F in January 1948. The coldest year was 1940, which had an average annual temperature of 65.7°F. The warmest year was 1927, which had an average annual temperature of 71.3°F. The average annual rainfall for the period 1893–1955 was 57.82 inches. The wettest year was 1919, when there was 79.88 inches of rainfall; and the driest year was 1954, when there was 30.08 inches of rainfall. The annual precipitation at Lake Charles for the years 1893–1955 is shown on figure 2. During this period the greatest monthly rainfall was 17.9 inches in June 1947, and the least was 0.05 inch in October 1952. The normal monthly rainfall for the same period is shown on figure 3.

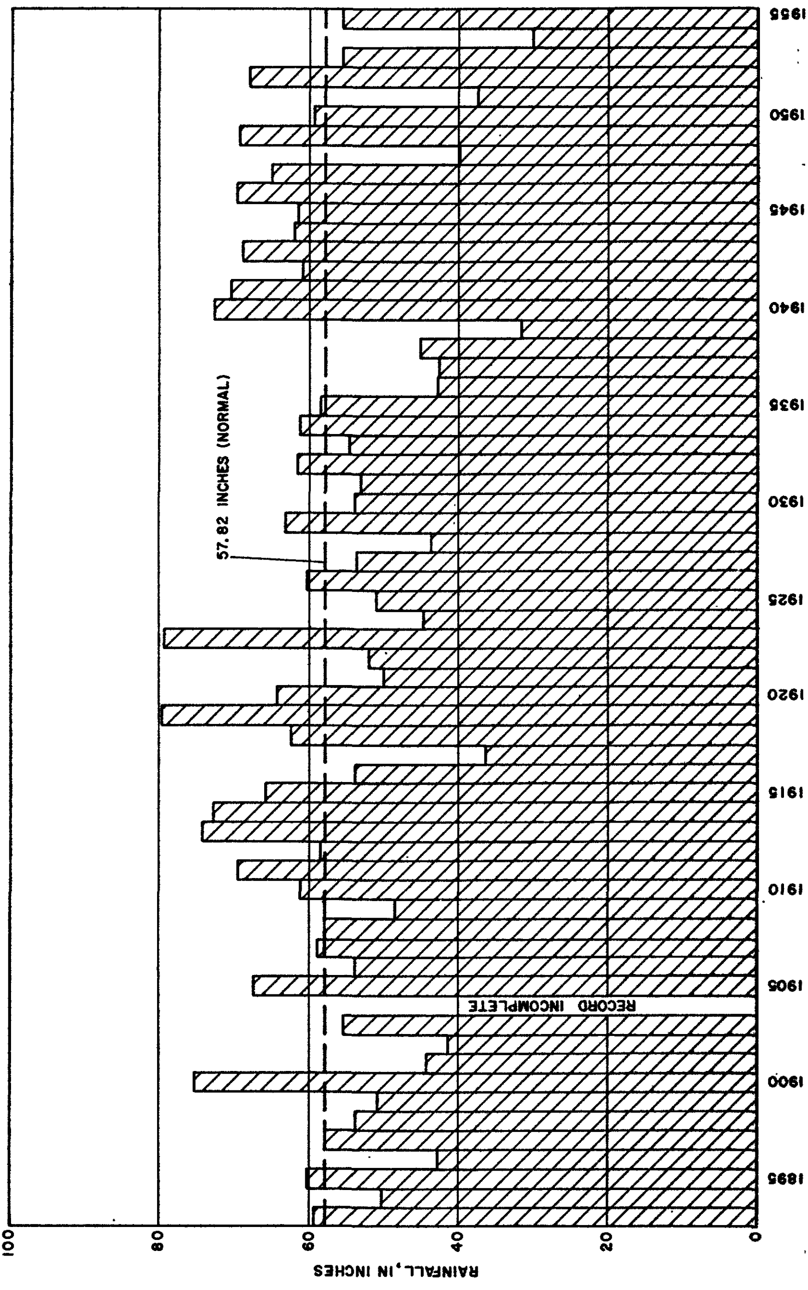

FIGURE 2.—Graph showing annual precipitation at Lake Charles, La., for the years 1893–1955.

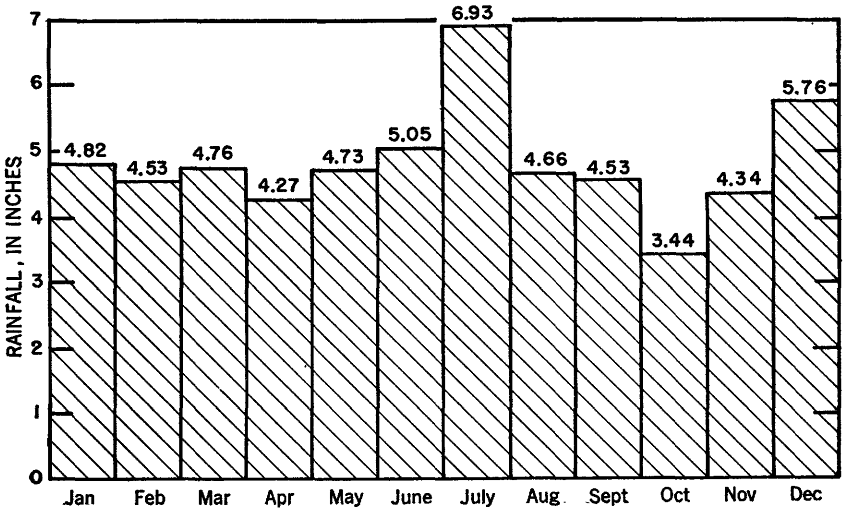

FIGURE 3.—Graph showing the normal monthly precipitation at Lake Charles, La., for the period 1893–1955.

GENERAL GEOLOGY

Calcasieu Parish lies within the Gulf Coastal Plain province and is immediately underlain by Recent and Pleistocene deposits of Quaternary age. (See table 1.) These deposits occur throughout southern Louisiana and parts of northern Louisiana. In Calcasieu Parish they are underlain by southward-dipping sedimentary rocks of Tertiary age, which crop out in Texas and northern Louisiana.

TABLE 1.—*Stratigraphic column of Calcasieu Parish showing sources of fresh ground water*

Era	System	Series	Formation	Faunal zone	Aquifer	Water-bearing properties
Cenozoic	Quaternary	Recent	Alluvium			Yields small supplies for domestic use. Water is generally hard and contains iron.
		Pleistocene	Prairie formation. Montgomery formation. Bentley formation. Williana formation.		Chicot: Shallow. "200-foot" "500-foot" "700-foot"	Large quantities of hard water available. Individual wells yield as much as 4,500 gpm.
	Tertiary	Pliocene	Foley formation		Evangeline	Yields small to moderate quantities of soft water, reportedly as much as 300 gpm.
		Pliocene(?) and Miocene.	Fleming formation of Fisk (1940).	*Rangia johnsoni, Potamides matsoni.*		Contains fresh water in northern part of parish.
		Miocene(?)	Catahoula formation.	*Discorbis, Heterostegina, Marginulina.*		Contains no fresh water.

The outcrop belts of the sedimentary rocks of Quaternary and Tertiary age roughly parallel the gulf coastline from Texas to Florida except in the Mississippi River embayment area.

The surface contacts between the deposits of Recent and Pleistocene ages are not well defined everywhere, but in many places they are marked by a scarp or a slight change in the slope of the land surface and by dissimilar vegetation. However, because of similar lithologic character and lack of distinctive fossils, the deposits in the subsurface usually are extremely difficult to differentiate.

DEPOSITS OF RECENT AGE

Deposits of Recent age occur along the southern edge of the parish and in the Sabine and Calcasieu River valleys and some of their tributaries. These deposits were laid down in the Gulf of Mexico and in the valleys of streams. They generally consist of fine sand, silt, clay, and a few thin lenses of coarser sand. The deposits range from narrow belts along small streams to a maximum width of about 5 miles in the Calcasieu River basin.

DEPOSITS OF PLEISTOCENE AGE

Deposits of Pleistocene age crop out in almost all parts of Calcasieu Parish. During Pleistocene time, ice covered the northern part of the North American Continent at least four times. As a result of each of these glaciations, sea level was lowered and gulf-coast streams cut valleys while adjusting to new base levels. Melting of the ice resulted in great quantities of sediment being carried by streams southward from the glaciated areas and deposited on the Gulf Coastal Plain. This stream-transported sediment now forms a thick blanket over much of central and southern Louisiana. Fisk (1940, p. 175) identified and named four different depositional terraces (table 1) in north-central Louisiana which he correlated with the fluctuations of sea level during Pleistocene time. Three of these terraces—the Prairie, the Montgomery, and the Bentley—are exposed at the surface in Calcasieu Parish. The youngest terrace, the Prairie, covers most of Calcasieu Parish, extending from the southern edge to the Houston River. It occurs also along the Sabine and Calcasieu River valleys to the northern boundary of the parish. The Montgomery terrace extends northward from the Houston River to a northeast line about 2 miles north of DeQuincy. The Bentley terrace is present in a small area about 2 miles northwest of DeQuincy. During the course of this study, no evidence was found that the subsurface deposits correlate with these terraces.

In a report on the ground-water resources of southwestern Louisiana, Jones (Jones and others, 1954, p. 138) named the system of aquifers formed by the Pleistocene deposits "the Chicot reservoir." To eliminate confusion with surface-water reservoirs, the name has been modified to "Chicot aquifer." (See table 1.) Generally, the Chicot aquifer consists of thick deposits of gravel, sand, and clay grading from fine material at the top to coarser material at the base. The base of the Chicot aquifer is usually identified as the base of the deepest gravel layer penetrated by wells (Jones and others, 1954, p. 62). In Calcasieu Parish the principal fresh-water-bearing sands are the "200-," "500-," and "700-foot" sands, so named for the depths at which they occur in the Lake Charles industrial district (Jones, 1950). Although these sands are separate hydrologic units in most of Calcasieu Parish, they become one hydrologic unit just outside the northeast boundary of the parish. In Calcasieu Parish the base of the "700-foot" sand is considered to be the base of the Chicot aquifer. This correlation is the same as that determined from previous studies. In the industrial district the base of the Chicot aquifer, or Pleistocene deposits, is 900 feet below mean sea level. This conforms closely to determinations made by Fisk (1944, fig. 70) and Jones and others (1956, pl. 8), who show the contact between the Pleistocene and Tertiary deposits to be about 1,000 feet below sea level in the industrial district.

DEPOSITS OF PLIOCENE AGE

Underlying the Chicot aquifer in Calcasieu Parish is the Evangeline aquifer, which consists of a series of fine to medium sand, silt, and clay within the Foley formation of Pliocene age (Jones and others, 1956, p. 51). Typically these sediments are lignitic and are gray and blue to black as contrasted with the rusty-brown and buff sediments of the overlying Pleistocene strata. There are no known diagnostic markers, lithologic or fossiliferous, that enable correlation of the beds with others. According to Jones and others (1954, p. 57), the Foley formation lies near the surface in northern Beauregard, Allen, and Evangeline Parishes, where it is covered by a thin veneer of Pleistocene deposits. From this area the formation dips southward and is present throughout southwestern Louisiana.

The upper part of the Miocene beds immediately underlying the Foley formation is marked by the clam *Rangia* (*Miorangia*) *johnsoni*. Fisk (1944, fig. 68) maps the top of the Miocene beds at a depth of about 2,500 feet below mean sea level at Lake Charles. As the base of the deposits of Pleistocene age is about 700 feet below mean sea level (pl. 4), the Pliocene deposits are considered to be about 1,800 feet thick at Lake Charles. The data presented by Jones and others (1956, pl. 8) and Fisk (1944, fig. 68) indicate that the thickness of the Evangeline aquifer generally increases toward the south in Calcasieu Parish. At DeQuincy in the northern part of the parish, the thickness is about 1,000 feet. Considerable additional data are needed to establish definitely the age and correlation of sedimentary rocks of Pliocene age in Calcasieu Parish.

DEPOSITS OF MIOCENE AGE

Underlying the Pliocene deposits are the Fleming formation of Fisk (1940) and the Catahoula formation of Miocene(?) age. The top of the *Rangia johnsoni* faunal zone is used to mark the top of the Miocene rocks by gulf-coast geologists (Fisk, 1944, fig. 68). These formations generally consist of lenticular beds of gray sand, silty clay, and clay that have a total combined thickness of about 7,000 feet at DeQuincy (Fisk). However, because no water wells penetrate these deposits in Calcasieu Parish, formation samples for either lithologic or faunal determinations were not available for study.

STRUCTURE

Calcasieu Parish lies near the east-trending axis of the gulf-coast geosyncline, which coincides approximately with the Louisiana coastline. During subsidence of the geosyncline throughout Cenozoic time, thick wedge-shaped deposits of clay, silt, sand, and gravel were laid down. These deposits are thickest (about 30,000 feet) along the axis of the geosyncline.

Regional faulting of sedimentary rocks as young as Pleistocene has occurred in Calcasieu Parish in the vicinity of the Houston River (Jones and others, 1954, p. 100). Local deep-seated faults are commonly found during exploration for oil. Generally these faults have an eastward trend. This faulting may be related to: the Cascadian revolution (a period of considerable widespread crustal disturbance), which began in Miocene time and lasted well into late Pleistocene time; crustal instability related to the subsidence that is occurring south of the Cameron-Calcasieu Parish line and the uplift occurring north of this line (Howe and others, 1935, p. 37); and local penetration of salt plugs into the strata of Pleistocene age (Howe and others, 1935, p. 87).

Structural features such as salt domes show a marked effect on the occurrence of fresh ground water. (See pl. 9.) In Calcasieu Parish there are 24 oil or gas fields, of which 6 are associated with salt domes—the Starks, Edgerly, Sulphur Mines, Iowa, Vinton, and Lockport. Some of these salt plugs have risen to within 1,200 feet of the surface and have resulted in faulting of the overlying and surrounding strata. These faults probably are restricted to the vicinity of the dome. Evidence of possible faulting in the vicinity of the Starks dome is indicated by the occurrence of salt-water-

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bearing sand at a depth of less than 300 feet below sea level. (See pl. 9.) The irregularity of deposition during the Pleistocene with regard to thickness and distribution of individual beds makes the delineation of fault zones extremely difficult. Much more information is needed to establish definitely the exact geologic and hydrologic relationship existing between geologic structural features and fresh-water aquifers.

GENERAL HYDROLOGY

OCCURRENCE OF GROUND WATER

Ground water may be defined as that part of the subsurface water in the zone of saturation (Meinzer, 1923, p. 38). It is the water that is available to wells or is discharged through springs. The source of essentially all ground water is precipitation in the form of rain or snow; part of this precipitation runs off from the surface of the ground directly into lakes or streams, part is returned to the atmosphere by evapotranspiration, and the remainder percolates down to the water table, replenishing the aquifers. Ground water is discharged from aquifers by means of wells; by movement into overlying or underlying aquifers; by springs; by effluent seepage to streams, canals, and lakes; and by evapotranspiration where the water table is near the land surface.

Ground water occurs under water-table conditions in areas where the water falling on the land surface can percolate downward through pore spaces in the ground to the zone of saturation. The upper surface of this zone of saturation is the water table. (See fig. 4.) Artesian conditions exist where the water-bearing formation

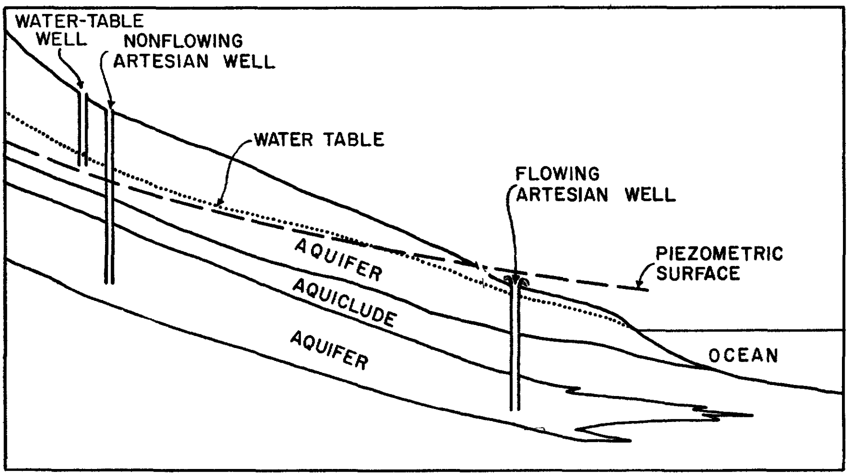

FIGURE 4.—Idealized section showing water-table and artesian conditions.

(aquifer) is overlain by a less permeable formation (aquiclude) and the water in the aquifer is under hydrostatic pressure, rising above the aquifer in wells penetrating it. The piezometric surface is an imaginary surface representing the height, with reference to a common datum such as sea level, to which water will rise in a well tapping an artesian aquifer. Throughout Calcasieu Parish the water in the principal water-bearing sands is under artesian pressure and thus, although not flowing, the wells in these sands are considered to be artesian wells.

HYDRAULIC CHARACTERISTICS

The amount of water that a material can hold is a direct function of its porosity. Where the pore spaces are large and interconnected, as they commonly are in sand and gravel, water is transmitted more or less freely, and the material is said to be permeable. Where the pore spaces are small, as in clay, water is transmitted slowly and the clay is said to be semipermeable or impermeable. Alluvial deposits of sand and gravel usually are very permeable and are considered good aquifers. Clay and silt deposits are relatively impermeable and are considered poor aquifers, even though they usually have a higher porosity than sand and gravel. A measure of the ability of a material to transmit water is given by the field coefficient of permeability (P_f), which may be defined as the rate of flow of water in gallons per day through a cross-sectional area of 1 square foot under a hydraulic gradient of 100 percent at the prevailing ground-water temperature. The field permeability (P_f) multiplied by the thickness of the aquifer (m), in feet, is equal to the coefficient of transmissibility (T). The coefficient of transmissibility usually is determined in the field by pumping tests and may be defined as the number of gallons of water transmitted in 1 day through a vertical strip of the aquifer 1 foot wide having a height equal to the saturated thickness of the aquifer under a hydraulic gradient of 100 percent at prevailing ground-water temperature. Under certain conditions the coefficient of storage (S) may be determined concomitantly with the coefficient of transmissibility. The coefficient of storage of an aquifer represents the volume of water released from storage or taken into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. These two coefficients are the principal hydraulic characteristics of an aquifer used in computations of ground-water flow.

PUMPING TESTS

The data obtained from pumping tests using one or more observation wells are used to calculate transmissibility and storage coefficients. Theis (1935, p. 519–524), utilizing an analogy of the flow of ground water to the flow of heat by conduction, developed the nonequilibrium formula for computing the coefficients of storage and transmissibility. The formula is—

$$s=\frac{114.6Q}{T}\int_{\frac{1.87r^2S}{Tt}}^{\infty}\frac{e^{-u}}{u}du \qquad (1)$$

where—

s is drawdown, in feet, at observation well
Q is discharge, in gallons per minute
T is coefficient of transmissibility, in gallons per day per foot
r is distance, in feet, from observation well to pumped well
S is coefficient of storage
t is time, in days, since pumping started.

The Theis nonequilibrium formula assumes that the aquifer is of infinite areal extent and uniform thickness and is homogeneous and isotropic (conducts water with equal facility in all directions), that the coefficients of transmissibility and storage in the aquifer remain constant at all times and places, that the pumped well is of infinitesimal diameter and completely penetrates the aquifer, and that water is released from storage instantaneously with a decline in artesian head. From the formula, it is apparent that the rate of drawdown in an observation well is directly proportional to the discharge rate of the pumping well. Therefore, for any value of transmissibility and storage at any time and distance, an increase or decrease in the discharge rate will cause a proportionate increase or decrease in the theoretical drawdown; for example, doubling the discharge rate will double the theoretical drawdown.

During this study, pumping tests were made in the winter when pumping for irrigation was negligible and industrial requirements were at a minimum, and a maximum number of observation wells could be used without adversely affecting normal operations. However, despite determined efforts of well owners to regulate pumping, it was not possible to make long-period pumping tests because of varying discharge rates caused by the breakdown of equipment and fluctuations in normal line pressure. During the tests, discharge measurements were made by means of water meters, orifices, Cox flowmeters, and the trajectory method. Depth-to-water measurements in wells were made by using electric tapes, steel tapes, and water-stage recorders readable to the nearest hundredth of a foot. For a period before each test, water levels were measured to determine the water-level trend, for use in adjusting the water-level drawdown or recovery data obtained during the test.

The coefficients of transmissibility and storage were determined as follows (Wenzel, 1942, p. 87): The adjusted drawdown or recovery values were plotted against time on logarithmic paper and the resulting curve was matched, by superposition, with a type curve derived from the Theis nonequilibrium formula. After matching with the type curve, values of $W(u)$, u, drawdown (s), and time (t) were obtained for substitution in the formula. To facilitate computations, these values were determined by selecting a match point on the observed data graph where $W(u)$ and u are equal to 1. A typical plot of observed data and its relation to the type curve is shown in figure 5.

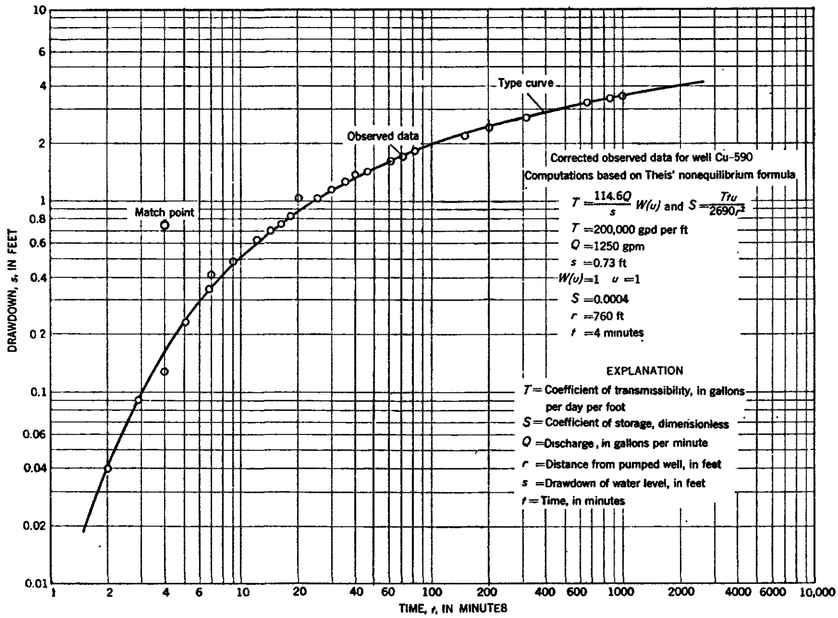

FIGURE 5.—Graph of results obtained from a pumping test in well Cu-590 in the Lake Charles industrial district.

The Theis formula, as modified by Ferris (1948) and by others, can be used to determine the presence of hydrologic boundaries. However, owing to test-time limitations no effects of hydrologic boundaries, either recharge or barrier, were shown by the drawdown and recovery curves. Future pumping tests made over a longer period of time may indicate the presence of boundaries and supplement the available geologic and hydrologic information.

The calculated storage coefficients indicate that water in the "200-," "500-," and "700-foot" sands is under artesian conditions. The values of transmissibility, permeability, and storage calculated from data obtained during pumping tests, length and type of tests, wells used, owners, aquifers tested, and sand thicknesses are listed in table 2. As the coefficient of transmissibility is a function of the

TABLE 2.—*Summary of transmissibility, permeability, and storage coefficients as determined by pumping tests*

Well	Owner	Sand thickness (feet)	Coefficient of transmissibility (gpd per ft)	Field coefficient of permeability (gpd per sq ft)	Coefficient of storage	Duration of test (minutes)	Date	Method
"200-foot" sand								
Cu- 88 [1]	Continental Oil Co	123	120,000	950	------------	379	10-14-43	Recovery.
90 [1]	do	116	75,000	660	------------	233	10-11-43	Do.
497	F. Helms	175	270,000	1,520	0.00082	260	2- 3-55	Drawdown interference.
497	do	175	270,000	1,520	.00082	260	2- 3-55	Recovery interference.
633	G. Natly	175	260,000	1,500	.00091	250	2- 3-55	Do.
633	do	175	260,000	1,500	.00091	250	2- 3-55	Drawdown interference.
"500-foot" sand								
Cu- 33 [1]	Greater Lake Charles Water Co	125	140,000	1,080	0.00060	1,463	2-10-44	Recovery.
76	Firestone Tire & Rubber Co	170	180,000	1,060	.00031	1,350	10-11-54	Drawdown interference.
76	do	170	180,000	1,090	.00057	1,300	10-11-54	Recovery interference.
95	Cities Service Ref. Corp	160	180,000	1,160	.00051	1,160	10-11-54	Drawdown interference.
95	do	160	200,000	1,240	.00064	820	10-11-54	Recovery interference.
97	Petroleum Chemicals, Inc	165	180,000	1,090	.00037	1,390	10-11-54	Drawdown interference.
97	do	165	200,000	1,180	.00043	1,020	10-11-54	Recovery interference.
263	M. Drost	140	150,000	1,070	.00059	300	11-10-54	Do.
263	do	140	140,000	960	.00060	300	11-10-54	Drawdown interference.
445	Cities Service Ref. Corp	153	210,000	1,370	.00025	250	10-11-54	Recovery interference.
459	Olin Mathieson Corp	135	160,000	1,150	.00065	430	3- 7-55	Drawdown interference.
459	do	135	160,000	1,190	.00068	410	3- 7-55	Recovery interference.
585	Jefferson Lake Sulphur Co	230	280,000	1,220	.0011	580	7-14-54	Do.
585	do	230	280,000	1,220	.0011	680	7-14-54	Drawdown interference.
590	Cities Service Ref. Corp	160	180,000	1,160	.00033	1,360	10-11-54	Do.
590	do	160	200,000	1,220	.00049	1,000	10-11-54	Recovery interference.
624	Davison Chemical Co	140	140,000	960	.00045	390	11- 9-54	Do.
624	do	140	130,000	930	.00041	350	11- 9-54	Drawdown interference.
Cn- 59 [2]	R. Stine	210	220,000	1,020	.00062	170	12-13-54	Do.
Be-359 [3]	S. Caldwell	290	560,000	1,950	.00011	300	12-15-54	Recovery interference.

"700-foot" sand

Cu- 3 [1]	Greater Lake Charles Water Co.	140	160,000	1,180	----------	1,316	2- 7-44	Recovery.
36	do	140	180,000	1,250	0.00028	1,260	2- 7-44	Recovery interference.
36	do	140	180,000	1,320	.00037	1,320	2- 9-44	Drawdown interference.
37	do	140	180,000	1,250	.00023	1,260	2- 7-44	Recovery interference.
38	do	140	150,000	1,070	.0017	1,320	2- 9-44	Drawdown interference.
446	Cities Service Ref. Corp.	140	190,000	1,360	.00061	405	10-14-54	Recovery interference.

[1] Pumped well. [2] Well in Cameron Parish. [3] Well in Beauregard Parish.

aquifer's permeability and thickness, a thickening or thinning of the aquifer will, if the permeability is constant throughout the aquifer, produce a corresponding change in value of the coefficient of transmissibility. The effect on drawdowns caused by changes in the coefficient of transmissibility is shown on figure 6. Graphs

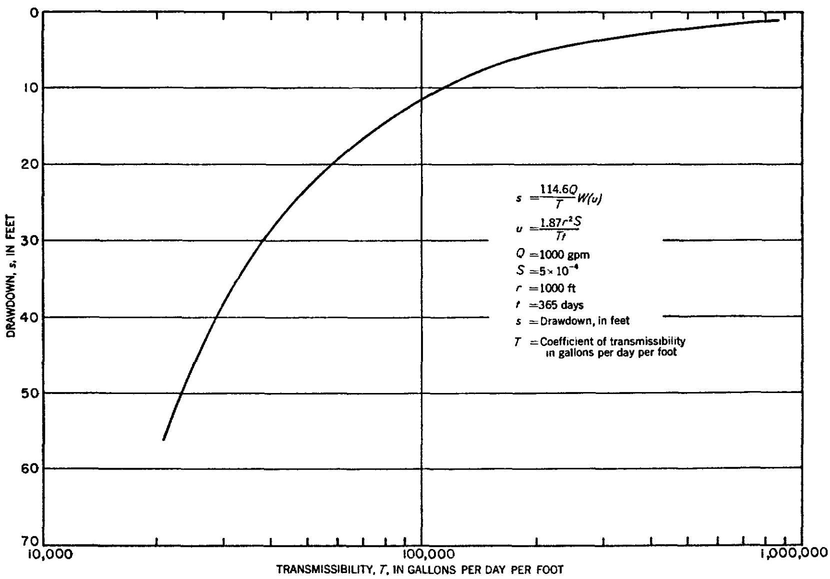

FIGURE 6.—Graph showing the theoretical drawdown in infinite aquifers having different coefficients of transmissibility.

showing the theoretical effects of pumping from aquifers having transmissibility and storage coefficients determined for each principal sand are included in the section "Rock formations and their water-bearing properties."

The effect on water levels of pumping in a well field also can be predetermined using the coefficients of transmissibility and storage. For example, in table 3 the drawdown of water levels are tabulated for a field consisting of four wells, 8 inches in diameter, tapping an ideal aquifer. These computations are based on the following assumptions: The distance between the wells is as shown in table 4; all wells started pumping simultaneously at a rate of 1,500 gpm each for 100 days; the coefficients of transmissibility and storage are 200,000 gpd per foot and 0.0005, respectively; and the wells have an efficiency of 100 percent.

A well assumed to be 100 percent efficient is a discharging well in which the water level is at the same level as that immediately outside the well—that is, a well in which there are no well-entrance losses. Because of construction factors, such as incomplete well

TABLE 3.—*Theoretical drawdown, in feet, in 4 wells pumping 1,500 gpm each for 100 days under assumed conditions*

Well	1	2	3	4
1	19.0	11.4	9.6	9.1
2	11.4	19.0	10.0	9.1
3	9.6	10.0	19.0	9.8
4	9.1	9.1	9.8	19.0
Total drawdown	49.1	49.5	48.4	47.0

TABLE 4.—*Distance, in feet, between wells listed in table 3*

Well	1	2	3	4
1	0	100	300	400
2	100	0	240	410
3	300	240	0	280
4	400	410	280	0

development and improper selection of screen apertures, the measured drawdown in a pumped well is usually greater than the theoretical drawdown.

SPECIFIC CAPACITY

The specific capacity of a well is defined as the yield per unit of drawdown of water level in the well for a given time. It is commonly expressed in terms of gallons per minute per foot of drawdown (gpm per foot). The specific capacity of a well is dependent primarily on the well's effective diameter, the degree of development or efficiency of the well, and the transmissibility of the formation.

Specific-capacity data may be used to:

1. Compare the capabilities of different aquifers to yield water to wells. Wells screened in the Chicot aquifer have average reported and measured specific capacities of 24 to 40 gpm per foot, whereas wells screened in the Evangeline aquifer have specific capacities ranging from 2 to 20 gpm per foot (Jones and others, 1954, p. 132). This difference indicates the greater ability of the Chicot aquifer to yield water to wells.

2. Measure the well efficiency or determine the adequacy of well development. Specific capacities determined during the course of development of a new well will increase to an optimum value, depending on the hydraulic characteristics of the aquifer and on the construction of the well. On the basis of the average coefficients of transmissibility and storage determined for the "500-foot" sand in the industrial district, a 12-inch well, 100 percent efficient, has a theoretical specific capacity of 80 gpm per foot at the end of 1 day of continuous pumping. The observed specific capacities of "500-

foot" wells generally are about 40 gpm per foot. Theoretically, therefore, the wells have an average efficiency of about 50 percent.

3. Determine optimum pumping rates. Figure 7 is a plot of specific capacity and discharge for well Cu–95, an industrial well in Calcasieu Parish. It shows that as the pumping rate increases above 600 gpm the specific capacity decreases. The decrease, probably the result of a change from laminar to turbulent flow in the vicinity of

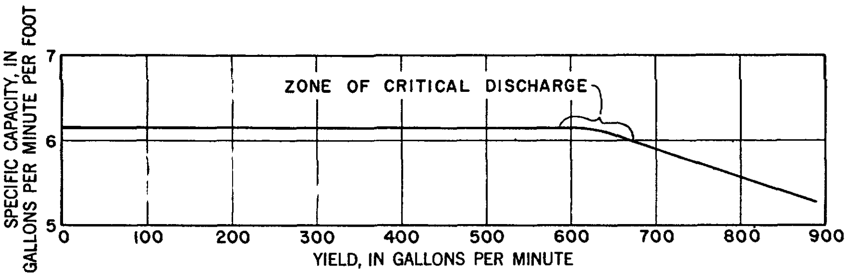

FIGURE 7.—Graph showing relation of specific capacity and yield of well Cu–95.

the well screen, indicates the critical discharge or optimum pumping rate for well Cu–95 to be about 600 gpm.

4. Indicate whether the decline in yield of a well is caused by well or pump failure. If the yield of a well declines but the specific capacity remains unchanged, the decline in yield is the result of declining areal water levels or faulty pumping equipment, whereas, if a decline in yield is accompanied by a decrease in specific capacity, the efficiency of the well has declined and the need for redevelopment is indicated. For example, in 1942 the specific capacity of well Cu–95 was 32 at a yield of 1,500 gpm, and in 1956 the specific capacity was about 6 at an optimum yield of 600 gpm. (See fig. 7.)

WATER-LEVEL FLUCTUATIONS

Water levels in wells penetrating an artesian aquifer fluctuate continuously, owing to pumping and to natural causes such as barometric and tidal changes, and natural discharge. Changes in barometric pressure are usually reflected as diurnal and longer term changes of water levels in wells. Changes in tide level often produce subdued changes of water level in wells adjacent to tidal waters. An increase in barometric pressure produces a decline of the water level in an artesian well, by forcing water out of the well into the aquifer. Conversely, a rise in tide level produces a rise in water levels in artesian wells because of the increased load and consequent compression of the aquifer. Another loading effect that may cause water levels to fluctuate in wells is the weight of trains that pass nearby. Water-level fluctuations and the effects of a passing train are shown on the hydrograph for well Cu-77 (fig. 8). The small jogs, or vertical lines, are caused by rapid compression of the aquifer when the trains are passing the well. The larger decline and subsequent recovery of water levels shown on figure 8 were caused when nearby wells were turned on and off.

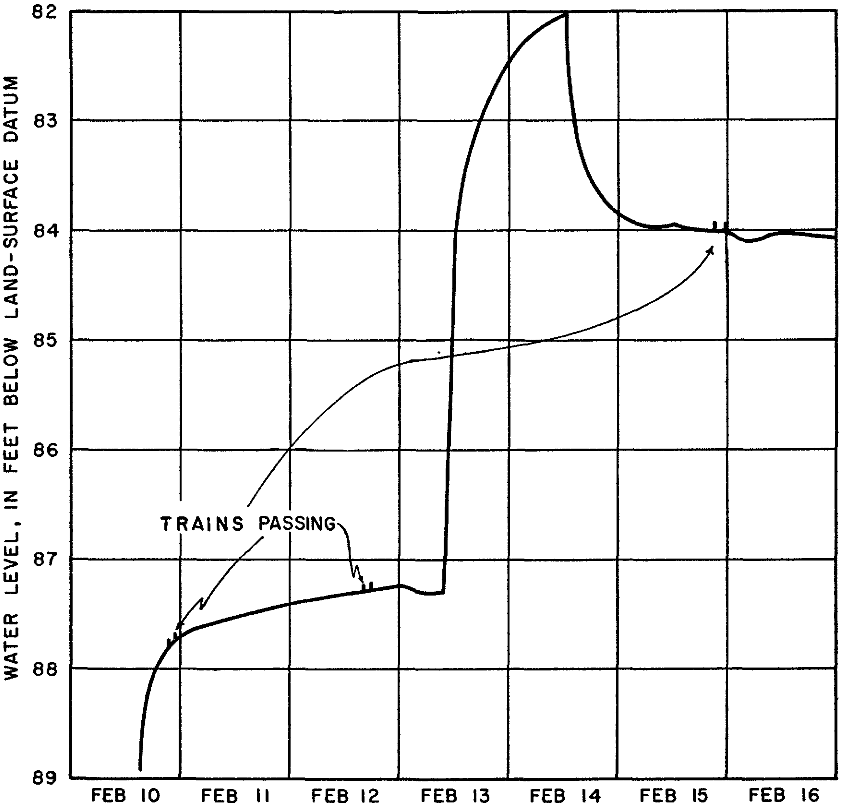

FIGURE 8.—Graph showing water-level fluctuations in well Cu-77 for the period February 10-16, 1955.

Although shallow water-table wells are directly and rapidly affected by changes in the amount of rainfall, there have been no observed water-level changes in wells in the "200-," "500-," and "700-foot" sands in Calcasieu Parish due to normal variations in precipitation. However, changes in temperature and rainfall affect the quantities of water used; this indirectly affects the water levels. Water levels in wells are lowest during the summer when water use is highest. The period of low levels may or may not coincide with a period of low rainfall.

RECHARGE AND DISCHARGE

Recharge to water-bearing sands in Calcasieu Parish is from precipitation and by movement of ground water into the parish from surrounding areas.

Recharge to the shallow sands of Recent age is by the movement of water from the land surface downward to the water table. Water levels in wells penetrating these deposits usually rise soon after a rain, especially when the soil is not dry enough to absorb all the water before it reaches the water table. Water levels in some water-table wells adjacent to streams rise and fall with stream levels, indicating that the stream serves both as a source of recharge and a means of discharge.

Recharge to the Chicot aquifer occurs principally in the outcrop areas in Beauregard, Allen, Rapides, and Evangeline Parishes. A part of the rainfall in these areas enters the aquifer and moves laterally to points of discharge. In general, the amount of water received is greater than the amount that can be transmitted downdip, and consequently the excess water is rejected in the recharge area. Many of the streams there, such as the Calcasieu River and some of its tributaries, are hydrologically connected to the aquifer and may serve as a source of recharge or an area of discharge.

The permeability of the clays within and above the Chicot aquifer has not been accurately determined. Locally, however, substantial amounts of recharge to the "500-foot" sand may occur by downward movement of water from the "200-foot" sand, or by upward movement from the "700-foot" sand, through clays in areas where the piezometric surface in the "500-foot" is lower than that in the "200-" and "700-foot" sands. A quantitative estimate of recharge from these sources is given elsewhere in the report under "Vertical movement" in the section "Depth of occurrence of fresh ground water."

Discharge from the Chicot aquifer occurs by natural means and by pumping from wells. In the recharge area of the aquifer, the rejected recharge is discharged naturally into streams; and where the water level is near the land surface, large quantities of water are discharged by evapotranspiration. Prior to the start of intensive pumping of wells in Calcasieu Parish, discharge also occurred downdip by vertical leakage of water through the confining beds into other aquifers, into streams, and into the Gulf of Mexico.

Recharge to the Evangeline aquifer occurs in its outcrop area where rain falls on the exposed surface. The water then moves downdip in the aquifer to points of discharge. Discharge from this aquifer in Calcasieu Parish is principally by upward movement through overlying beds into the Chicot aquifer. The amount of water moving from the Evangeline aquifer into the Chicot aquifer is not now known, but it depends on the thickness and permeability of the intervening beds and the head differential between the aquifers.

QUALITY OF WATER

The mineral matter in fresh ground water is derived from the soil and rocks through which the water passes. All minerals are soluble in water to some extent; common salt is readily soluble, whereas quartz is considerably less soluble. Limestone is soluble in water containing carbon dioxide. Because fresh ground water moves very slowly through some rocks, there is adequate time for solution to take place and the water to become mineralized. If a velocity of 0.5 foot per day is assumed, water entering the aquifer in southern Beauregard Parish and removed from the ground in central Calcasieu Parish, a distance of 24 miles, would have nearly 700 years in which to assimilate rock materials. Generally, water-bearing sands containing large quantities of calcium, magnesium, iron, and aluminum minerals yield hard water, and aquifers composed of pure quartz sand will yield soft water. Some hard waters may become softened by passing through sediments containing natural zeolites, which exchange adsorbed sodium for the calcium and magnesium in the water.

Water samples from selected wells throughout the parish were collected and analyzed. The results of analyses made available by companies in the industrial district are included in table 7 in addition to the results of analyses made in the Quality of Water laboratory, Austin, Tex., of the U.S. Geological Survey and field determinations of chloride.

The concentrations of certain dissolved constituents in drinking water (U.S. Public Health Service, 1946, p. 371–384), which preferably should not be exceeded in potable water used on interstate carriers, are shown below:

Constituent	*Concentration (ppm)*
Iron and manganese (Fe and Mn)	0.3
Magnesium (Mg)	125
Sulfate (SO_4)	250
Chloride (Cl)	250
Dissolved solids	500

A concentration of dissolved solids of 1,000 ppm is permissible if water of better quality is not available. The concentration of fluoride must not exceed 1.5 ppm.

The National Research Council (Maxcy, 1950) in relating nitrate concentrations to the occurrence of methemoglobinemia (blue baby disease) recommends an upper limit of 44 ppm of nitrate as NO_3 in water used for infant feeding.

Because the amount of salt in irrigation waters in southwestern Louisiana is often expressed as grains per gallon, figure 9 was prepared so that the concentration of chloride in parts per million can be converted approximately to grains per gallon of sodium

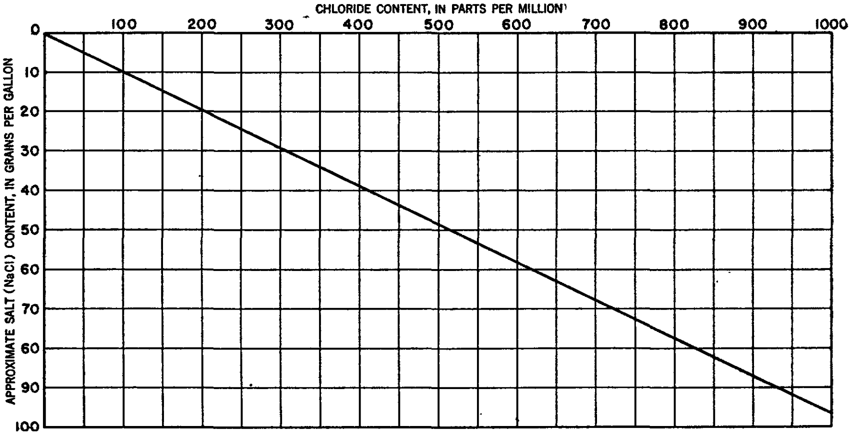

FIGURE 9.—Chart for converting parts per million of chloride to grains per gallon of sodium chloride (NaCl).

chloride. This conversion graph is based on the assumption that all the chloride present in the water is the result of the solution of sodium chloride.

TEMPERATURE OF GROUND WATER

The temperature of ground water is often of great importance to industries contemplating use of the water. Ground water usually has a more uniform temperature than surface water; consequently, it is more desirable for certain industrial uses. The temperature of water from the 3 principal aquifers in Calcasieu Parish ranges from 70° to 79°F. Temperatures of water pumped from wells in the "200-," "500-," and "700-foot" sands are shown in figure 10. The variations of temperature in wells of the same depth may be due to friction in the pump and casing, method of measurement, entrance of water at different levels in different wells penetrating the same sand, or slight local variations in temperature at the same depth at different places in a given aquifer. A line drawn through the greatest concentration of points indicates that there is a 1°F rise in temperature for about each 70-foot increase in depth. This thermal gradient is in general agreement with that determined in other sections of Louisiana (Meyer and Turcan, 1955, p. 72).

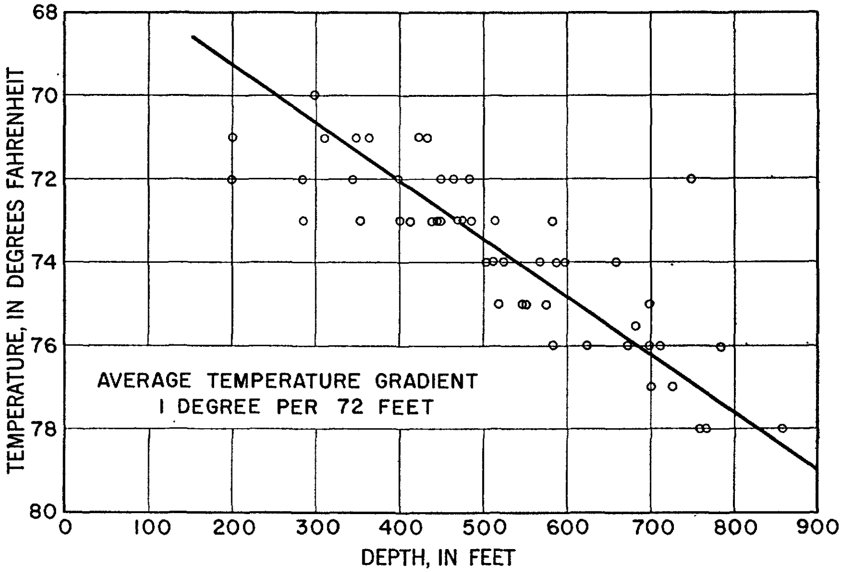

FIGURE 10.—Chart showing the temperature of ground water with relation to depth.

ROCK FORMATIONS AND THEIR WATER-BEARING PROPERTIES

Ground water occurs in deposits of Recent, Pleistocene, Pliocene, and possible Miocene age in Calcasieu Parish. These deposits, consisting of unconsolidated gravel, sand, silt, and clay, contain fresh water to maximum depths ranging from about 250 feet to about 2,500 feet.

The deposits of Recent age are of small areal extent and supply only small quantities of water to wells. The deposits of Pleistocene age contain thick, extensive water-bearing beds that supply practically all the ground water used in Calcasieu Parish. In the northern part of the parish, deposits of Pleistocene age contain fresh water throughout their entire thickness, whereas in the southern part salt water is present in the lower part of the deposits. Data from electrical logs of oil-test wells indicate that the deposits of Pliocene age contain fresh water only in the extreme northern part of Calcasieu Parish. At present there are no known fresh-water wells screened in these deposits in Calcasieu Parish; however, because of the lack of necessary data it is difficult to correlate exactly the various formations in the vicinity of DeQuincy with known aquifers to the south, and it is possible that the sands below a depth of 500 feet (at DeQuincy) are of Pliocene age. Deposits of this age supply moderate quantities of water in Beauregard, Allen, and Evangeline Parishes.

DEPOSITS OF RECENT AGE

Shallow wells in deposits of Recent age supply small quantities of water in Calcasieu Parish. These wells are generally less than 50 feet in depth and yield an average of only 2 to 3 gpm. The sands in which the wells are bored or dug range from 1 to 10 feet in thickness and are local in extent. The exact thickness and areal extent of the sand phase of the Recent deposits has not been determined; consequently, it is difficult to estimate the hydrologic characteristics and potential yields of these deposits. The water is moderately hard and in some places is contaminated, as indicated by a chloride content as high as 1,300 ppm.

DEPOSITS OF PLEISTOCENE AGE

Locally in Calcasieu Parish there are shallow beds of Pleistocene age in the Chicot aquifer which provide small quantities of water for domestic and stock uses. However, the principal water-bearing sands in the Chicot aquifer in Calcasieu Parish are the "200-foot," the "500-foot," and the "700-foot" sands. (See pls. 3 and 4.) The "200-foot" sand supplies water to irrigation and public-supply wells in the eastern part of the parish and to several industrial wells in the central part of the parish. It is also the primary source for domestic wells. The "500-foot" sand is the most heavily developed aquifer in the parish and is the principal source of ground water for industrial needs and irrigation. The "700-foot" sand supplies water to the cities of Lake Charles and DeQuincy, to a few nearby industries, and to irrigators in the south-central part of the parish.

CHICOT AQUIFER

SHALLOW SANDS

A few wells in the southern and central areas of the parish reportedly yield water from a bed of oyster shells and associated beds of silty sand, which occur locally at depths of about 100 feet. These beds usually yield small quantities (less than 100 gpm) of hard water for rural supplies. Locally shallow sand lenses, penetrated by bored, dug, or drilled wells, supply small quantities of ground water for domestic and stock uses throughout the parish. Two wells at the Lake Charles Air Force Base are used for watering animals and have yields of 50 gpm. The amount of water withdrawn from these deposits is probably less than a quarter of a million gallons per day and is not considered in the section on "Withdrawals and their effects."

Locally, water from shallow wells adjacent to streams containing salt water may become contaminated when the stream levels are higher than the ground-water levels. It has been reported that some shallow wells in the vicinity of the Houston River yielded water of high chloride content. However, there is no apparent contamination of the underlying sands from this source, as indicated by the chemical analyses of water from the "200-foot" sand in this vicinity (table 7).

"200-FOOT" SAND

Distribution and thickness.—The "200-foot" sand, as shown by the fence diagram (pl. 3) and cross sections *A–A′* and *B–B′* (pl. 4), extends under the entire parish but is irregular in thickness and depth. In general, the sand is thickest in the southeastern part of the parish. For example, the log of well 26 (pl. 3) shows the sand to be 200 feet thick, and that its top is at a depth of 180 feet. At the eastern edge of the parish the sand is 190 feet thick and occurs at a depth of 85 feet. (See well 8, pl. 3; well 20, pl. 4.) In the industrial district, well Cu–92 (well 16, pl. 4) shows the sand to be 70 feet thick and to occur at a depth of 165 feet. At the western edge of the parish the sand is 20 feet thick in well 12 (pl. 4) and is at a depth of 175 feet. Although not shown on plates 3 and 4, the "200-foot" sand in the southwestern part of Calcasieu Parish splits into two, three, or more separate sands. The general dip of the top of the "200-foot" sand is southward at a rate of 4 to 10 feet per mile; however, rapid changes in thickness may locally cause the dip to vary considerably, as in the southwestern part of the parish were it increases to 50 feet per mile. (See pl. 6.) The outcrop and recharge area of the "200-foot" sand is in northern Calcasieu and southern Beauregard Parishes, where in many places it is covered by a clay layer up to 75 feet thick. Where the clay layer is very thick, probably little recharge occurs; however, where it is quite thin or nonexistent, large amounts of water can move down into the sand. It is probable that permeable deposits, contained in the old stream valley now occupied by the upper reaches of the West Fork of the Calcasieu River, locally penetrate through the clay layer and provide a means of recharge to the "200-foot" sand when ground-water levels are below stream levels.

Generally, the "200-foot" sand grades from fine to medium sand at the top to a coarse sand or gravel at the base. In some places, as at Sulphur, the finer materials predominate; in the vicinity of Holmwood, however, there is a complete sequence from fine to coarse sand. The results of mechanical analyses of formation samples from well Cu–560, in the industrial district, are presented in figure 11. The sand grains making up the formation are dominantly subangular quartz grains slightly iron stained, with a small percentage of dark minerals. Where present, the gravel is made up of chert pebbles.

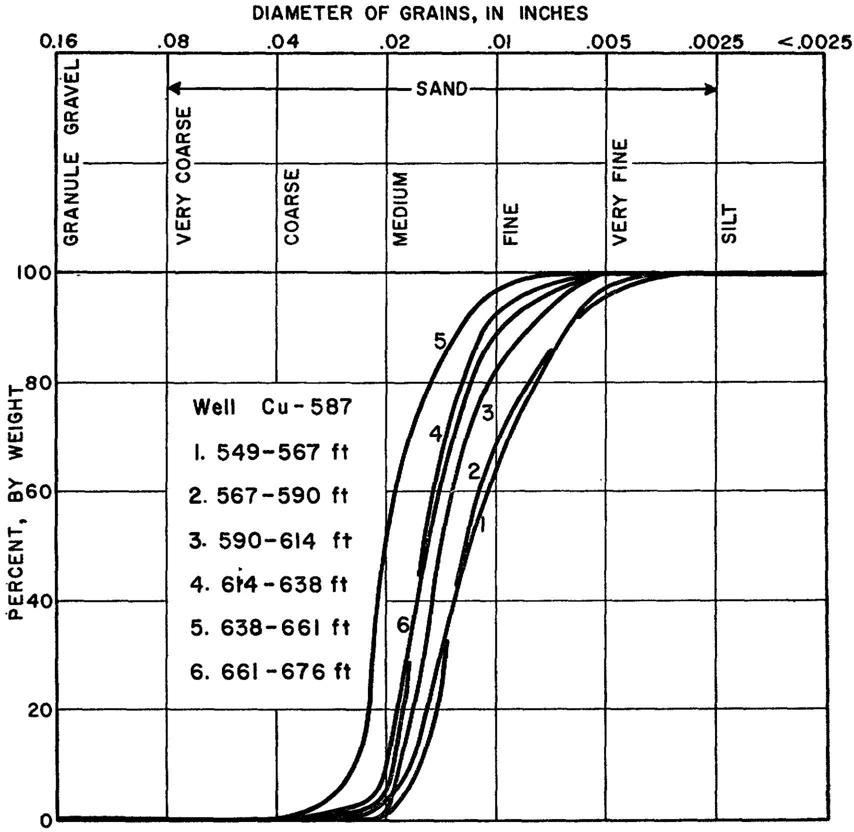

FIGURE 11.—Cumulative curves showing grain size of materials from the "200-foot" sand.

Hydrology.—The "200-foot" sand is used mainly to supply water for domestic and irrigation purposes. In the western part of Calcasieu Parish where the aquifer is thin, it provides water only for domestic use; in the central part it provides water for industrial use. In the eastern part of the parish, it is the principal source of water for irrigation and public supply.

Within the industrial district there are two large-capacity wells in the "200-foot" sand. One well had a reported specific capacity of 50 gpm per foot of drawdown at a yield of 2,000 gpm when installed in 1940. In the eastern part of the parish, where the "200-foot" sand supplies most of the water used for irrigation, yields of 10 wells listed in table 7 range from 1,800 gpm to 4,500 gpm and average 2,800 gpm. The results of a pumping test using wells Cu-90 and Cu-88 (at Westlake) indicate an average permeability of 800 gpd per square foot for the "200-foot" sand in the industrial district (table 2). The average coefficients of transmissibility (T) and storage (S) determined from a test using wells Cu-497 and Cu-633 in the vicinity of Holmwood are 260,000 gpd per foot and

0.00086, respectively. The average permeability of the "200-foot" sand in this area is 1,500 gpd per square foot. The variation in permeability in the "200-foot" sand is typical of the Chicot aquifer throughout southwestern Louisiana and is usually due to texture changes. At Holmwood, where the texture of the aquifer grades from fine to coarse sand, the permeability is about 60 percent greater than at Westlake, where the aquifer is composed primarily of finer materials.

The curves in figures 12 and 13 were computed by using the above-mentioned average coefficients of transmissibility and storage determined for the "200-foot" sand in the Holmwood area. These curves do not take into consideration hydrologic boundaries and changes in the character of the aquifer that might exist. The distance-drawdown curve in figure 12 shows that a well pumping 1,500 gpm for 100 days would cause a theoretical drawdown of about 6.0 feet at a distance of 1,000 feet. The time-drawdown curve (fig. 13) shows that a well pumping 1,500 gpm for 1,000 days would cause a drawdown of 7.5 feet at a distance of 1,000 feet.

Quality of water.—Chemical analyses of water from the "200-foot" sand are given in table 7. The water generally is of the sodium bicarbonate type, but it contains sufficient calcium and magnesium as to make it moderately hard to hard. Generally the iron content is less than 1 ppm; however, locally it may be as high as 8.5 ppm, as shown by the analysis for well Cu–347. The temperature of the

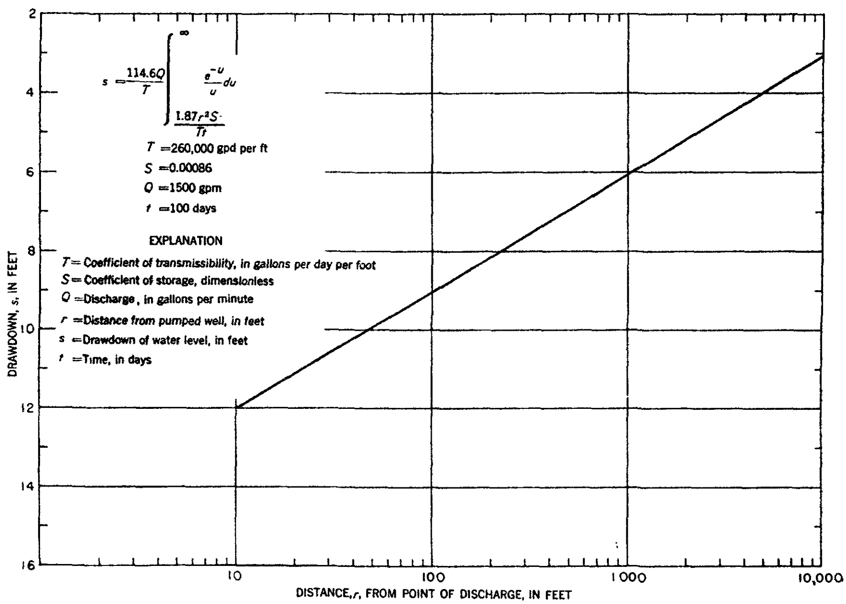

FIGURE 12.—Theoretical distance-drawdown relationship in an infinite aquifer having the hydraulic characteristics determined for the "200-foot" sand.

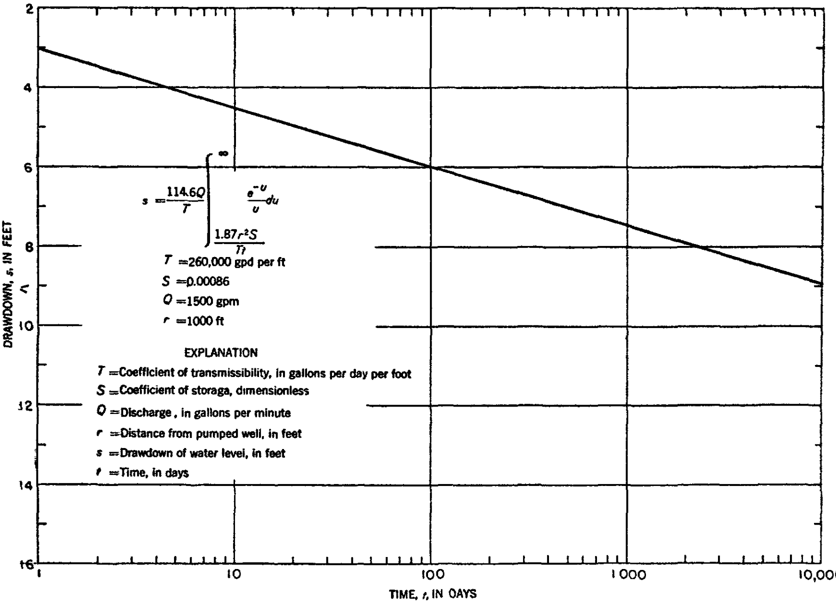

FIGURE 13.—Theoretical time-drawdown relationship in an infinite aquifer having the hydraulic characteristics determined for the "200-foot" sand.

water averages about 72°F. The chloride content of water from this sand is generally less than 100 ppm, except in the eastern part of the parish where it is as much as 300 ppm and the dissolved solids are as high as 700 ppm. (See analyses for wells Cu–347, Cu–640, and Cu–642.)

"500-FOOT" SAND

Distribution and thickness.—The "500-foot" sand is the principal aquifer in Calcasieu Parish. Its distribution throughout the parish is illustrated by cross sections *A–A′* and *B–B′* (pl. 4) and the fence diagram (pl. 3). The aquifer has a maximum thickness of 310 feet in the north-central part of the parish, as shown by the log of well 13 on plate 4, and a minimum thickness of about 25 feet in the southeast corner of the parish, as shown by well 26 on plate 3. The variation in thickness throughout the parish is shown by isopach contours on plate 7. The exact correlation of the "500-foot" sand northward from Sulphur to the parish line is tentative, owing to the irregularity of the beds and a lack of adequate subsurface information. In the southwest corner of Calcasieu Parish, the "500-foot" sand is between the depths of 590 and 750 feet; at Vinton it is between the depths of 410 and 600 feet and contains a clay layer between 470 and 500 feet. Within the industrial district the sand is about 170 feet thick between the depths of 390 and 560 feet in well Cu–74, and 200 feet thick (including a 10-foot clay bed) between the depths of 330 and 530 feet in well 16 (pl. 4). At well 1 (pl. 4), in the vicinity of DeQuincy, the "500-foot" sand is about 195 feet thick between the depths of 165 and 360 feet, and at Iowa, in the eastern part of the parish, it lies between the depths of 440 and 500 feet. (See well 20, pl. 4.)

Southwest of the industrial district, at well Cu–453, there is a sand between the depths of about 170 and 345 feet which appears to be of local extent; however, a study of water levels measured in this well indicates that it is hydrologically connected with the "500-foot" sand.

The "500-foot" sand dips southward from the outcrop area in central Beauregard and Allen Parishes at an average rate of 18 feet per mile. North of the industrial district, the average rate of dip is 18 feet per mile, whereas south of this area it increases to about 40 feet per mile. Locally the dip may vary considerably, owing to the unevenness of both the top and the bottom of the aquifer.

The material composing the "500-foot" sand is gray to brownish and usually ranges from fine sand at the top to coarse sand and gravel near the base. Results of the mechanical analyses made of sand samples from the "500-foot" sand are shown on figure 14.

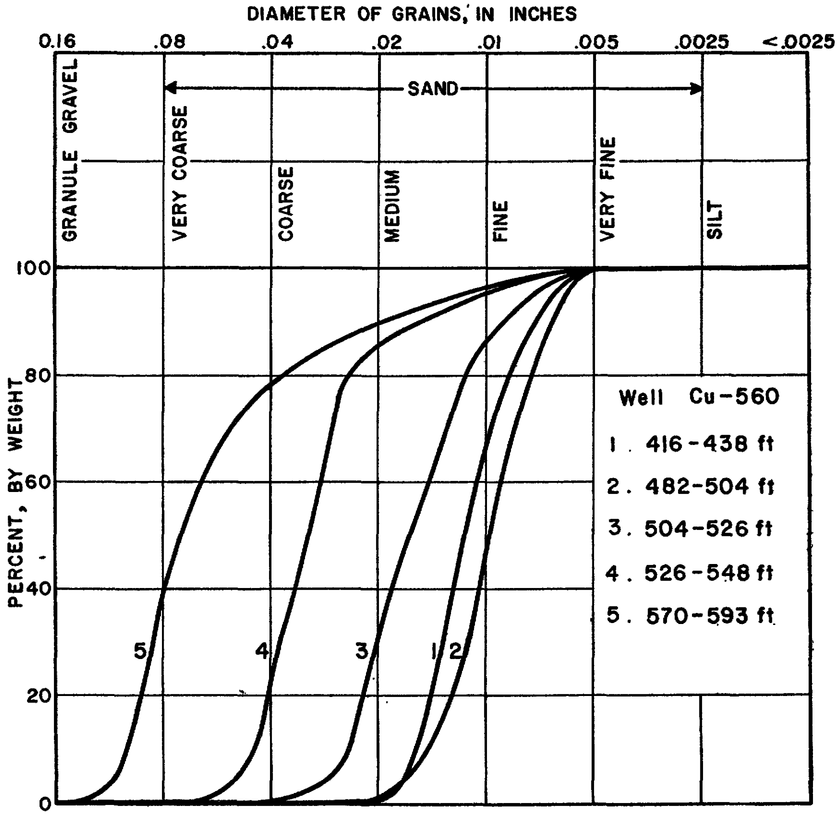

FIGURE 14.—Cumulative curves showing grain size of materials from the "500-foot" sand.

The sand consists dominantly of subangular quartz grains (a few iron-stained) and some dark minerals. The gravel is composed mostly of chert pebbles. Chunks of carbonized wood are often found in drill cuttings from layers where large logs were deposited with the sand and gravel. (See driller's log of well Cu–653 in table 8.)

Hydrology.—The "500-foot" sand is the most heavily developed aquifer in Calcasieu Parish. (See table 5.) It supplies water to the towns of Sulphur, Edgerly, and Vinton, La., and Orange, Tex.; to a large number of irrigation wells in the area; and to most of the industries. The amount of water withdrawn from the "500-foot" sand for each use in 1955 is given in table 5. The "500-foot" sand is not utilized to a large extent as a source of supply in the southeastern part of the parish, where it is relatively thin and consists of fine sand.

Reported yields from industrial wells screened in the "500-foot" sand range from 600 to 2,000 gpm. The reported specific capacities of industrial wells range from about 6 to 75 gpm per foot of drawdown and average 40. Irrigation wells, pumped to open discharge generally have greater yields than industrial wells. For example, the measured yields from two irrigation wells, Cu–635 and Cu–639, were 3,800 and 2,500 gpm, respectively.

The hydraulic characteristics of the "500-foot" sand were determined by pumping tests made at six separate sites using existing industrial and irrigation wells. The values of the coefficients of transmissibility, storage, and permeability are given in table 2. In the industrial district the average values determined are coefficient of transmissibility, 190,000 gpd per foot; coefficient of storage, 0.00054; and coefficient of permeability, about 1,200 gpd per square foot. The permeability of the "500-foot" sand in the northern part of the parish as determined from a test made at well Be–359 (about half a mile northeast of well Cu–208) is about 2,000 gpd per square foot (table 2), whereas to the south in the vicinity of the Calcasieu-Cameron Parish boundary the permeability decreased to about 1,000 gpd per square foot. (See results of tests of wells Cu–263 and Cu–59 in table 2). This variation in permeability is due to textural changes within the "500-foot" sand from south to north, where the coarser materials predominate. The average coefficient of transmissibility determined from pumping tests for the "500-foot" sand in Calcasieu Parish is 200,000 gpd per foot, which compares reasonably well with that (300,000 gpd per foot) determined from a geometric analysis of piezometric maps (Jones and others, 1954, p. 149).

On the basis of the assumptions that the aquifer is homogeneous, infinite in areal extent, and without lateral boundaries, and making use of the above-mentioned coefficient of transmissibility of 200,000 gpd per foot and an average storage coefficient of 0.00054, the curves in figures 15 and 16 were prepared. The graph in figure 16 shows that after 1 year of continuous pumping at 1,500 gpm water

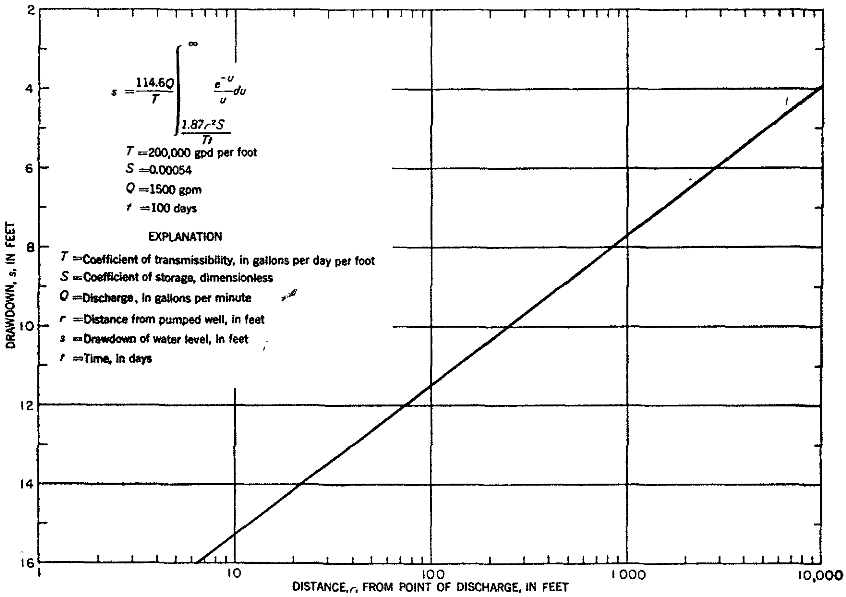

Figure 15.—Theoretical distance-drawdown relationship in an infinite aquifer having the hydraulic characteristics determined for the "500-foot" sand.

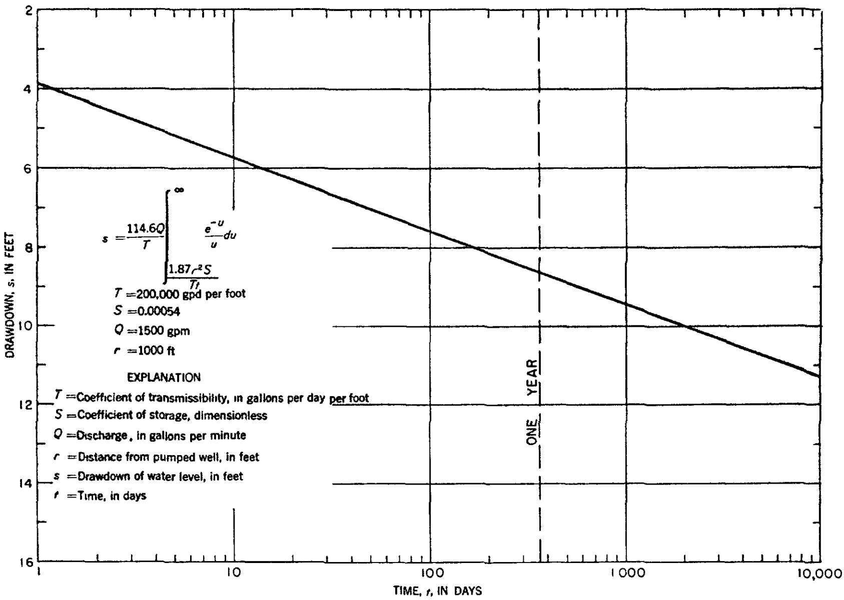

Figure 16.—Theoretical time-drawdown relationship in an infinite aquifer having the hydraulic characteristics determined for the "500-foot" sand.

levels at a distance of 1,000 feet from the pumping well would decline about 9 feet.

Quality of water.—Chemical analyses of water from wells screened in the "500-foot" sand (table 7) show the water to be moderately hard and to have a pH range from 6.7 to 8.6. The average of dissolved solids is 302 ppm and the chloride content is generally low in the northern and central parts of the parish where the average is about 30 ppm. Immediately south of the parish line in Cameron Parish, several irrigation wells yield water having a chloride content of 300 to 500 ppm. However, water samples collected in the southern part of Calcasieu Parish show no widespread salt-water contamination. Concentrations of chloride of more than 600 ppm are found locally above salt dome structures. (See analyses for well Cu-585 in table 7.) The total iron content ranges from 0.04 to 11 ppm, and the average for 28 samples (table 7) is 2.3 ppm. The temperature of the water averages 74°F.

"700-FOOT" SAND

Distribution and thickness.—The "700-foot" sand supplies water to industries and irrigators and is the source for public supply at Lake Charles. (See table 5.) The sand is at a depth of about 700 feet in the industrial district near Lake Charles. As shown by the fence diagram and the cross sections (pls. 3 and 4), the "700-foot" sand is rather thick and is continuous throughout the parish. In several places, clay layers divide the aquifer into two or three separate layers; however, because the clay layers are not continuous, the sands are considered to be hydrologically connected. The aquifer has a total thickness of 220 feet in the industrial district. (See well 7, pl. 4.) It is about 205 feet thick in the eastern part of the parish (see well 20, pl. 4), 90 feet thick in the western part of the parish (see well 16, pl. 3; well 11, pl. 4), and 60 feet thick in the vicinity of DeQuincy in the northern part of the parish (see well 1, pl. 4).

The regional dip of the sand between wells 1 and 10 on plate 4 is southward at about 10 feet per mile. The dip varies greatly, as shown by cross section *A–A'* (pl. 4) and by the contours drawn on the top of the "700-foot" sand shown on plate 8. In the central part of the parish, the dip is nearly flat as far south as the Sulphur mines in the vicinity of Sulphur, whereas in the area due south of Sulphur it increases to about 10 feet per mile. In the vicinity of Moss Lake, the rate of the southward dip increases to 50 feet per mile.

The "700-foot" sand is generally tan to grayish and grades from fine at the top to coarse at the bottom, as shown by the cumulative curves in figure 17. The grains are less iron stained and generally

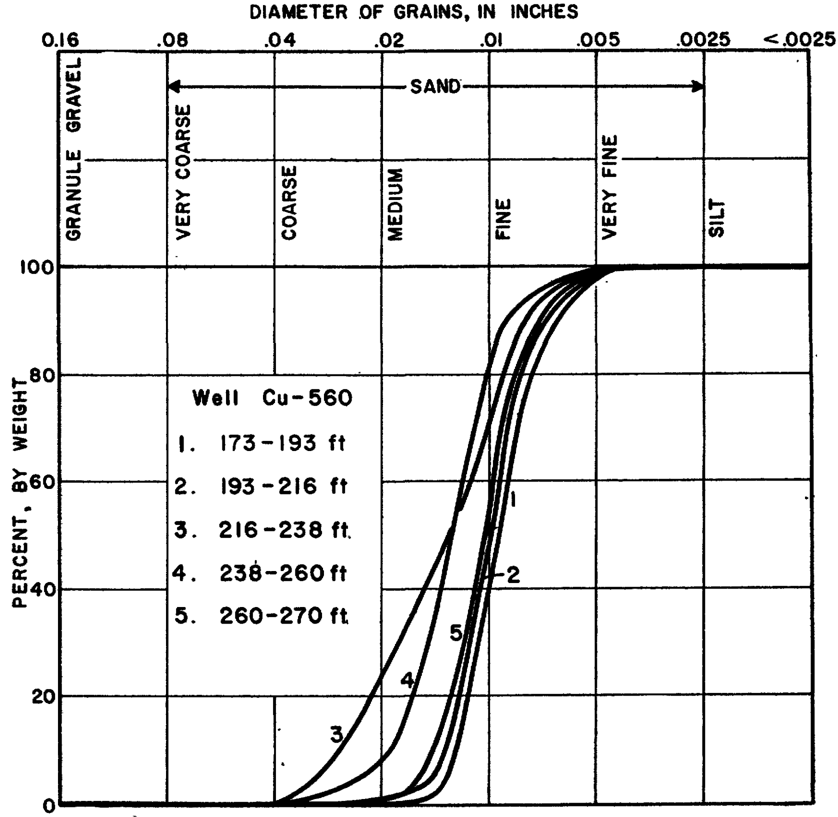

FIGURE 17.—Cumulative curves showing grain size of materials from the "700-foot" sand.

better rounded and finer than those in the "500-foot" sand.

Hydrology.—In 1955 there were eight large-capacity industrial wells screened in the "700-foot" sand. The city of Lake Charles derives its entire municipal water supply from six wells screened in this sand. The reported original yields from the municipal wells were about 1,200 gpm, and their reported specific capacities about 32 gpm per foot of drawdown. The reported yields of 15 industrial wells ranged from 800 to 2,200 gpm and averaged 1,500 gpm. The average specific capacity of 7 of these wells was 30 gpm per foot of drawdown.

Values of the coefficients of transmissibility and storage were determined in 1942 from wells owned by the Greater Lake Charles Water Co. (formerly Gulf States Utilities Co.). The average coefficient of transmissibility is about 180,000 gpd per foot, the average coefficient of storage is 0.0006, and the average permeability is 1,200 gpd per square foot.

The distance-drawdown and time-drawdown curves in figures 18 and 19 are based on coefficients of transmissibility and storage of

80,000 gpd per foot and 0.0006, respectively. As shown by the distance-drawdown curve (fig. 18), the drawdown in an observation well 1,000 feet from a well pumped at 1,000 gpm continuously for 10 days will be about 4 feet. The time-drawdown curve (fig. 19)

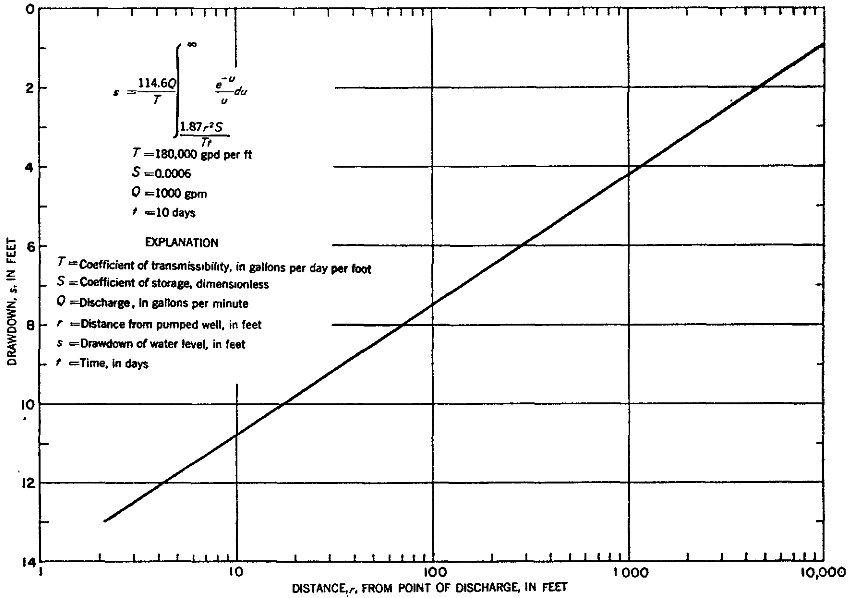

Figure 18.—Theoretical distance-drawdown relationship in an infinite aquifer having the hydraulic characteristics determined for the "700-foot" sand.

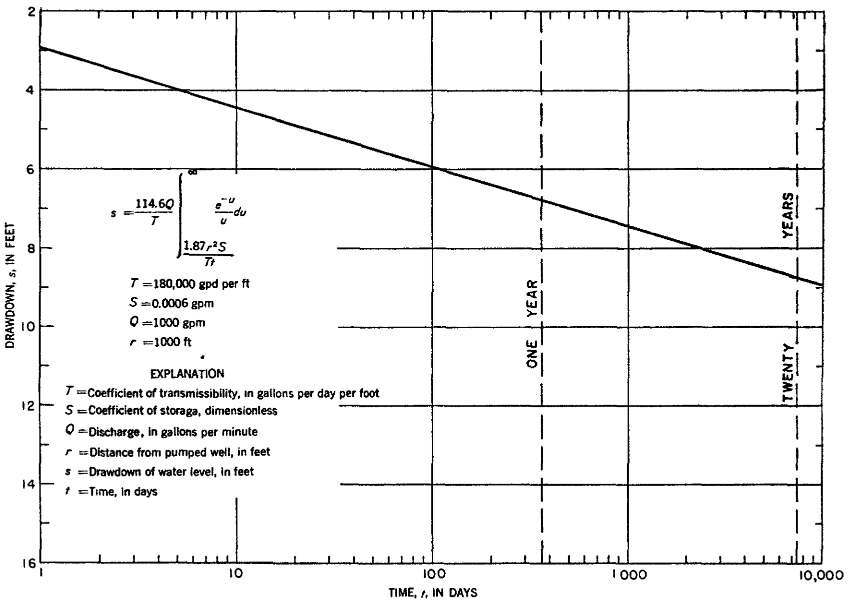

Figure 19.—Theoretical time-drawdown relationship in an infinite aquifer having the hydraulic characteristics determined for the "700-foot" sand.

shows that the drawdown in an observation well 1,000 feet from a well pumped at 1,000 gpm will be about 7 feet after 1 year of continuous pumping and that if pumped continuously for 20 years about 50 percent of the total drawdown will have occurred 10 days after the start of pumping.

Quality of water.—Chemical analyses of water from wells screened in the "700-foot" sand are given in table 7. Wells screened in this sand generally yield a moderately hard water that has a greater sodium-to-calcium ratio than that from the "500-foot" sand. The iron content averages about 3.2 ppm, and the temperature ranges from 74° to 78°F. Generally the chloride content of water in the "700-foot" sand is greater than that in the "200-" and "500-foot" sands. The curves in figure 20 indicate that there apparently has been no salt-water contamination of well Cu–463, which is screened in the "500-foot" sand in the industrial district, whereas the chloride content of water from well Cu–462, screened in the "700-foot" sand, has increased from about 25 ppm in 1950 to 220 ppm in 1955. Moreover, the chloride content in another nearby well screened in the "700-foot" sand (well Cu–96, fig. 20) had increased to 450 ppm when it was abandoned in 1951. The chloride content of the water from public-supply well Cu–3 had increased from 91 ppm in 1940 to 156 ppm in 1956. Well Cu–661, the most recently installed municipal-supply well in the southern part of the city of Lake Charles, yielded water having a chloride content of 88 ppm in September 1956. The chloride content of water from well Cu–151, an irrigation well screened in the "700-foot" sand in the southeastern part of the parish, was 316 ppm in 1955. The reason for the higher chloride content of water from these wells in the central and southern parts of the parish may be due to incomplete flushing of the "700-foot" sand by fresh water. In the northern part of the parish, the chloride content is less than 30 ppm (see analyses for wells Cu–7 and Cu–495 in table 7) and current records do not show any effects of salt-water encroachment.

DEPOSITS OF PLIOCENE AGE

EVANGELINE AQUIFER

Distribution and thickness.—The Evangeline aquifer is composed of sedimentary rocks of Pliocene age which occur throughout southwestern Louisiana. This aquifer is near the surface in northern Beauregard, Allen, and Evangeline Parishes, where it is overlain by a thin veneer of Pleistocene deposits (Jones and others, 1954, p. 57). In Calcasieu Parish it is difficult to identify accurately the top of the deposits of Pliocene age, as they bear a marked similarity to the overlying deposits of Pleistocene age. However, on the basis

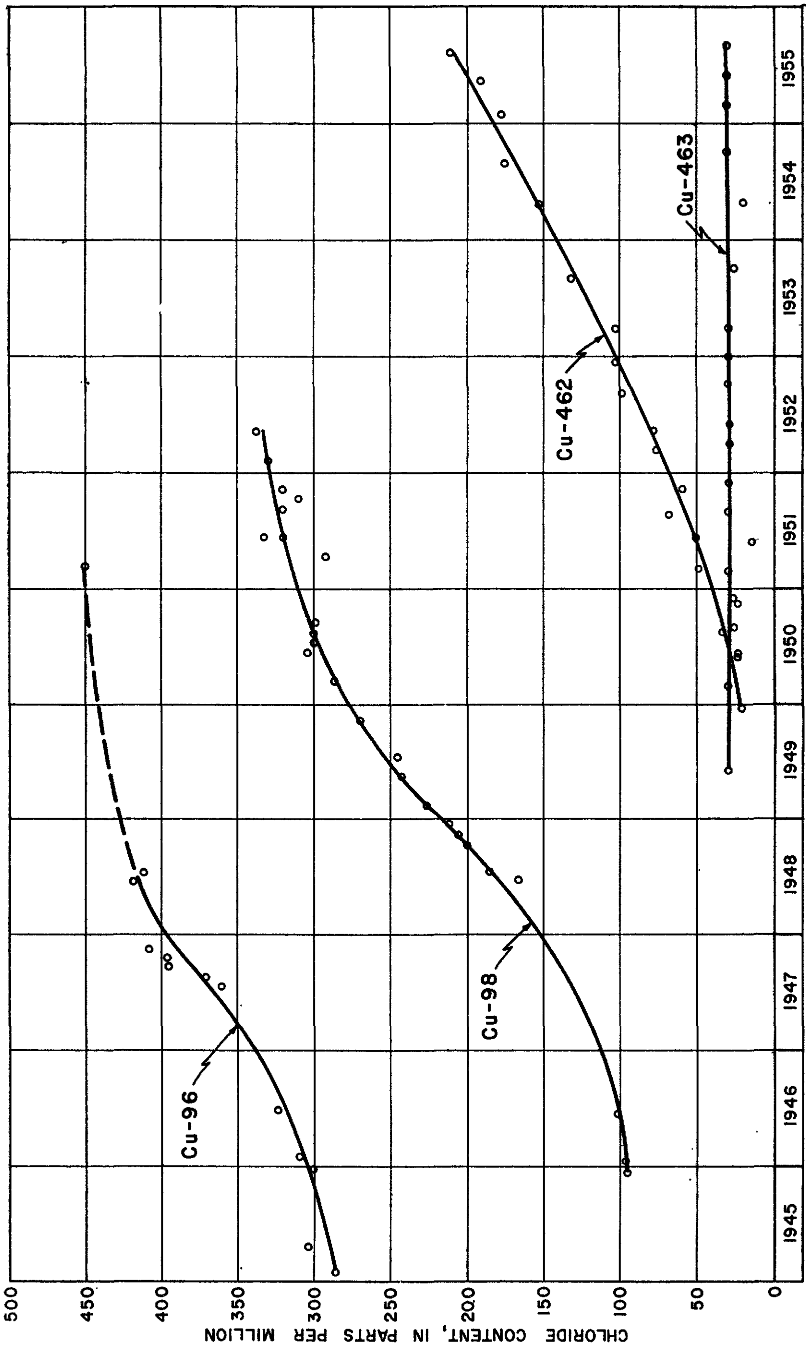

FIGURE 20.—Graph showing the chloride content of water from wells Cu-96, Cu-98, Cu-462, and Cu-463.

of changes in color and texture of the sediment (Jones and others, 1954, p. 69), the top of the Evangeline aquifer which is in the Foley formation, has been delineated and is shown in the geologic sections (pl. 4). In Allen and Evangeline Parishes, where several wells have penetrated the Evangeline aquifer, the sand generally is fine to medium grained. There is a considerable variation in the thickness of individual sand beds in the Evangeline aquifer. At DeRidder, in Beauregard Parish, 18 beds of sand in the lower part of the aquifer, between depths of 300 and 1,000 feet, range from 3 to 115 feet in thickness and average 27 feet (Jones and others, 1954, p. 130). Generally, the individual sand beds are discontinuous; however, it appears that each sand bed is connected either above, below, or laterally with other beds, thus forming a single hydrologic unit (Jones and others, 1954, p. 130). The Evangeline aquifer is about 1,000 feet thick in the vicinity of DeQuincy, where it contains fresh water. Southward, in the industrial district, it contains salt water throughout its entire thickness of about 2,000 feet.

Hydrology.—The permeability of the sands in the Evangeline aquifer (estimated to be 250 to 1,000 gpd per square foot) is generally lower than that in the overlying Chicot aquifer, as would be expected considering the finer grain of the materials making up these sands (Jones and others, 1954, p. 131). The specific capacity of 10 wells tapping the Evangeline aquifer in southwestern Louisiana ranged from 2 to 20 gpm per foot of drawdown, as compared to the average specific capacities of 24 to 40 gpm per foot of drawdown of wells in the Chicot aquifer. A test well (Cu–666) was drilled to a depth of 2,204 feet and was screened opposite a sand of Pliocene age between depths of 930 and 990 feet. The water level was 49 feet below the land surface, and the yield was 220 gpm—the specific capacity was 2. This is the only well known to have been screened in the Evangeline aquifer in Calcasieu Parish.

Quality of water.—In adjoining parishes where the Evangeline aquifer is a source of fresh water, the water is of the sodium bicarbonate type, very soft, slightly alkaline, low in chloride content, and free of excessive quantities of dissolved iron (Jones and others, 1954, p. 137). Where fresh it is excellent for public supply, although locally it may be yellowish or brownish. This color is probably due to colloidal organic matter, and the water generally is not considered harmful for human consumption.

As shown by data from electrical logs of test wells, the Evangeline aquifer contains salt water in the industrial district. The water from well Cu–666, near the industrial district, contains about 14,000 ppm of chloride; this substantiates data from electrical logs. In the northern part of the parish, the aquifer contains fresh water (having less than 250 ppm of chloride) throughout.

DEPOSITS OF MIOCENE AGE

Electrical logs of oil-test wells indicate that throughout most of Calcasieu Parish the sands of Miocene age contain salt water. However, according to electrical logs, fresh water occurs in a few thin sands of Miocene age between depths of 1,500 and 2,500 feet in the extreme northern part of the parish. Because no known water wells penetrate these sands in Calcasieu Parish, no information on their water-bearing characteristics is available.

WITHDRAWALS AND THEIR EFFECTS

GENERAL CONDITIONS

A total of about 105 mgd (million gallons per day) of water was withdrawn from wells in the principal sands of the Chicot aquifer in Calcasieu Parish in 1955. This estimate of withdrawal is based on ground-water use as reported by industries, measured discharge of some wells, and data supplied by municipalities. Of the 105 mgd pumped, about 66 mgd was used by industries, 27 mgd by irrigators, 8 mgd by municipalities, and 4 mgd for rural supplies. Of the 101 wells listed in table 6 as industrial-supply wells, 40 are for oil-field supply. Wells used for supply during drilling operations are temporary, and the present (1956) estimated pumpage from these wells is 0.25 mgd. This small amount is not listed in the total withdrawals in table 5.

Since 1955, rice has been included under the Federal price-support program. In Calcasieu Parish this program has resulted in a decline in rice acreage from an average of 77,000 acres a year during 1945–54 to about 63,000 acres a year during 1955–56. However, this decrease in acreage has not resulted in a significant decline in the amount of ground water used for irrigation. It appears that the total amount of water pumped is affected more directly by the amount of rain during the growing season than by the change in acreage planted. It is probable, however, that a continued decline in the acreage of rice will result in a general reduction in the amount of ground water pumped for irrigation. The relation of rainfall to pumpage for irrigation purposes from the Chicot aquifer

TABLE 5.—*Ground-water pumpage, in thousand gallons per day, in Calcasieu Parish in 1955*

Source	Municipal	Industrial	Irrigation	Rural	Total	Percent of total
"200-foot" sand	150	3,000	7,860	(?)	11,010	10.5
"500-foot" sand	1,700	50,700	17,000	(?)	69,400	66.0
"700-foot" sand	6,000	12,300	2,500	(?)	20,800	19.7
All sands (undifferentiated)				4,000	4,000	3.8
Total	7,850	66,000	27,360	4,000	105,210	
Percent of total	7.5	62.7	26.0	3.8		100

is shown in figure 21. The graph shows that pumping for irrigation generally is inversely related to rainfall during the rice-growing season. A comparison of rainfall and pumping for rice irrigation for 1954 and 1955 clearly illustrates this relationship. In 1954, when there was a total rainfall of 13.5 inches during the rice-growing season, about 53,000 acre-feet was pumped; in 1955 there was a total rainfall of 31 inches during the rice-growing season, and pumpage decreased to about 31,000 acre-feet. In 1954, moreover, 84,000 acres of rice was irrigated by 53,000 acre-feet of ground water, and in 1956 only 58,200 acres was irrigated, but the amount of ground water used increased to about 57,500 acre-feet. The rainfall during the rice-growing season in 1956 was 12.71 inches. The poor correlation for the years 1952 and 1953 is due to exceptionally heavy rains occurring within short periods of time during the rice-growing season. Because ground-water levels are directly affected by pumping, they declined rapidly during 1948 and 1951 (fig. 22) when rainfall during the growing season was below normal.

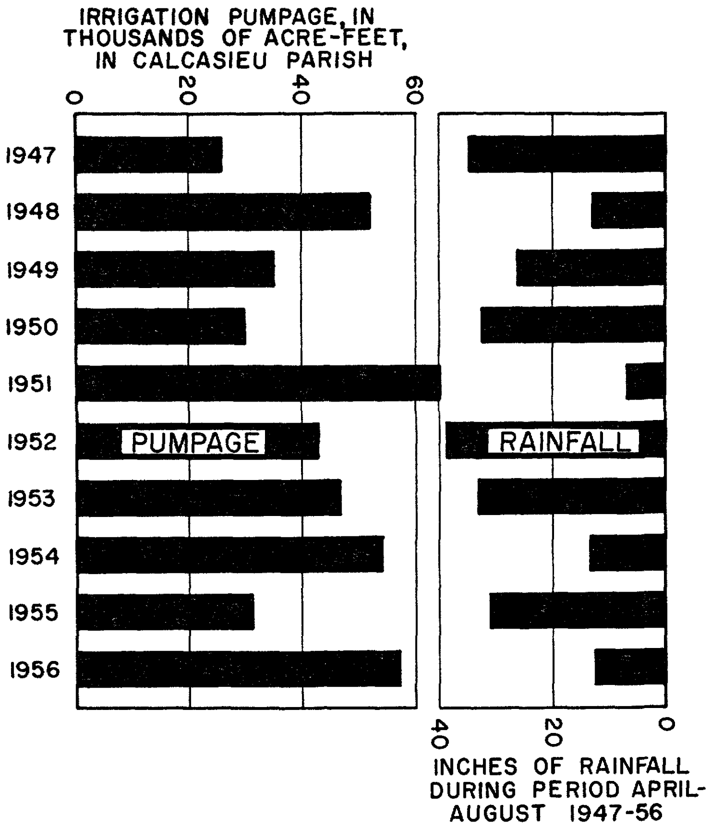

FIGURE 21.—Graph showing the relation between pumpage from the Chicot aquifer and rainfall during the rice-growing season.

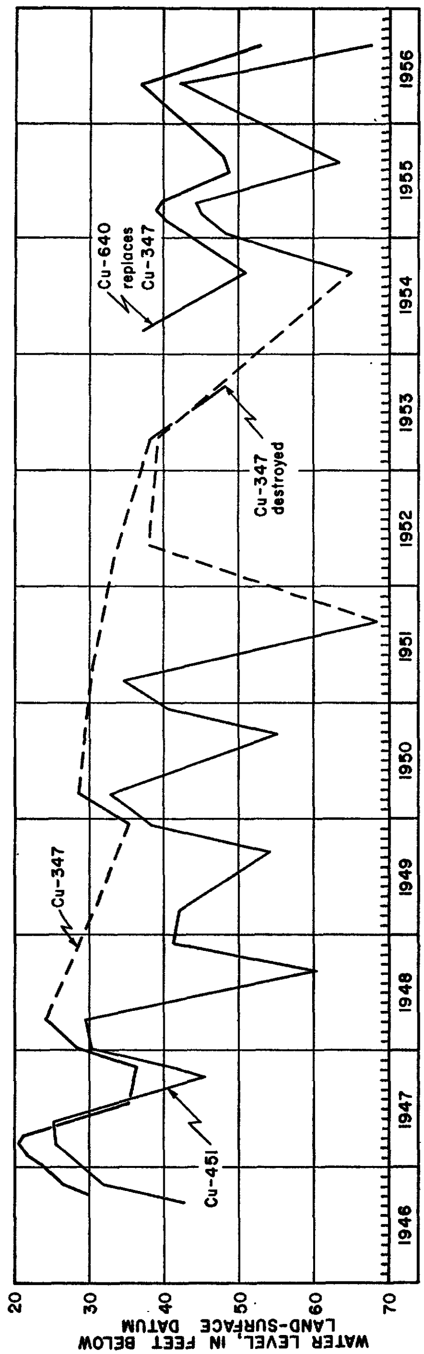

FIGURE 22.—Hydrographs of wells screened in the "200-foot" sand.

The quantity of water used from the Chicot aquifer for rural needs is based on an estimated per capita use of 125 gpd (Jones and others, 1954, p. 204) and a rural population of 32,133 (1950 census). This allows for gardening and stock supply and use by small businesses. It is reasonable to assume that practically all the water required for rural supplies is obtained from wells because of the availability and easy accessibility of a potable ground-water supply. All municipalities in Calcasieu Parish are dependent upon wells that tap the Chicot aquifer.

Practically all the ground water pumped in Calcasieu Parish is removed permanently from the aquifers. Water used is discharged into a network of drainage canals and streams which eventually flow to the Gulf of Mexico. There may be, and probably is, some local influent seepage from streams, and such recharge may include small quantities of used ground water. However, this amount is probably negligible and is not considered in the overall computation of ground-water use.

The concentration of pumping in the industrial district has resulted in this area having the lowest water levels in the Chicot aquifer in southwestern Louisiana. In the central part of this district the greatest water-level decline, to slightly more than 100 feet below sea level, has been in the "500-foot" sand. The average annual water-level decline in southwestern Louisiana is about 1 foot (Fader, 1957), whereas the present average annual decline in the principal sands in Calcasieu Parish is as great as 3.5 feet.

CHICOT AQUIFER

"200-FOOT" SAND

PUMPAGE

The first recorded well near Lake Charles in the "200-foot" sand was a drilled industrial well constructed prior to 1903 and was known as Reiser's Machine Shop well. It is reported that the altitude of this well was about 13 feet and that the well was known to flow to 17 feet above the land surface in 1903 (Harris and others, 1905, p. 59). The first large-capacity industrial well in this sand was constructed in 1940 near Westlake, La. Available records indicate that the "200-foot" sand supplied water to the first irrigation wells in the parish which were drilled about 1900 (Harris and others, 1905, p. 55–59). In the "200-foot" sand there are presently three large-capacity industrial wells in the vicinity of Westlake (pl. 2), in addition to public-supply and many irrigation wells in the southeastern part of the parish.

Withdrawals from the "200-foot" sand have gradually increased from little or nothing in 1900 to an average of about 11 mgd in 1955 (table 5). In 1955 the sand supplied 0.15 mgd for municipal purposes, principally at Iowa; 3.0 mgd for industrial purposes in the vicinity of Westlake; and 7.9 mgd for irrigation, principally in that part of the parish east of the Calcasieu River.

EFFECTS OF PUMPING

Water-level measurements made in wells screened in the "200-foot" sand are shown graphically on figure 25 and are reported in table 6. The measured water level in well Cu–45, in the city of Lake Charles, was 27.15 feet below the land surface on January 20, 1943, and 53.44 feet below land surface on March 18, 1956 (table 6); this decline of 26.29 feet during the 13-year period averages 2 feet per year. Southeast of Lake Charles, near Holmwood, the average yearly decline in well Cu–451 was 2 feet for the period 1947 to 1956 (fig. 22). The net water-level declines are computed from measurements made in the spring prior to the beginning of rice irrigation, as those measurements indicate more accurately the level of maximum recovery for the year. Since 1946 the average annual water-level decline has been less than 2 feet (see graphs for wells Cu–347 and Cu–640 on fig. 22) in the eastern part of the parish, where the "200-foot" sand is the principal source of water for domestic, agricultural, and municipal purposes. The water-level decline in well Cu–45 is closely representative of wells in the industrial district. Because of a pronounced decrease in the use of water for rice irrigation during 1955, the water levels showed a net recovery of as much as 3 feet from the spring of 1955 to the spring of 1956.

"500-FOOT" SAND

PUMPAGE

The first recorded drilled well in the "500-foot" sand was an industrial well 6 inches in diameter, owned by the Bradley and Ramsey Lumber Co. in Lake Charles. In 1903 this well had the largest natural flow (210 gpm) of any well in the State (Harris and others, 1905, p. 58). It is estimated that the static water levels in the "500-foot" sand in 1903 were about 20 feet above sea level. In 1934 pumpage from this sand was relatively small, and most of the wells flowed when completed. After the industrial expansion of the Lake Charles area (1934), pumpage gradually increased from a negligible amount in 1934 to 69.4 mgd in 1955, of which about 50.7 mgd (see table 5) was withdrawn from the "500-foot" sand for industrial purposes in Calcasieu Parish.

EFFECTS OF PUMPING

Water levels.—Throughout the parish, water levels in the "500-foot" sand have declined steadily during the period of record. In the area outside the industrial district, they declined at an average rate of about 2 feet per year during 1943–56, as shown by the hydrographs of wells Cu–115, Cu–120, Cu–208, and Cu–228 (fig. 23). The wells outside the area of heavy industrial and public-supply pumping reflect the regional water-level trend and seasonal declines caused by pumping for rice irrigation. The result of decreased seasonal pumping for rice irrigation in 1955 is shown graphically in figure 23; the 1956 spring water levels were higher than those measured the previous spring. The net water-level recovery in these wells for the year ranged from 2 to 4 feet.

In the industrial district, water levels declined at an average rate of about 1.4 feet per year during 1903–56; however, since 1934, when industrial development started on a large scale, water levels have declined at the average rate of about 2.9 feet per year. The average declines were based upon reported levels in 1903 and 1934 and measured levels in well Cu–22 (fig. 24) since 1943. This well is within the industrial district but in an area where the levels are not affected by nearby heavy pumping. The 1956 spring water levels in this well are about 3 feet below that measured in the spring of 1955. This suggests that the water-level fluctuations in well Cu–22 are caused primarily by variations in local industrial pumping.

The hydrograph (fig. 25) of water levels measured in well Cu–445 in the industrial district shows an average annual decline of about 5 feet during 1946–56. As shown in figure 25, the average daily municipal and industrial pumpage from the "500-foot" sand in the industrial district and adjoining communities in 1945 was 21 mgd, and in 1956 it was 53 mgd, representing an increase of 150 percent. The hydrograph of well Cu–445 reflects this increased pumping. The annual fluctuation, starting with a decline in the spring and ending with a recovery in the fall, is due to changes in industrial use as well as seasonal pumping for agricultural purposes.

Although the present decline of water levels in the areas of heavy pumping is relatively large, as compared to that in the other sands, it is not excessive and must be expected in order to provide a gradient sufficient to move the required amount of water into the areas of pumping. A wider spacing of wells, as new ones are drilled to replace old wells, would minimize the amount of interference between them. Moreover, if the total pumpage is not increased, wider spacing of wells will result in a decrease in the rate of water-level decline in the industrial district.

Analysis of piezometric map.—Calcasieu Parish is included in the area covered by piezometric maps for the year 1903 and the period 1944–51 in two recent reports, one (Jones and others, 1954) pub-

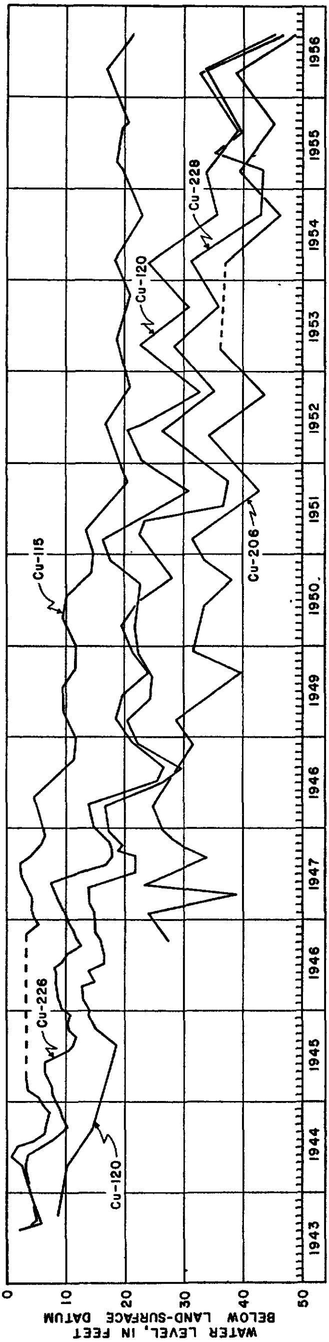

FIGURE 23.—Hydrographs of wells screened in the "500-foot" sand outside the industrial district.

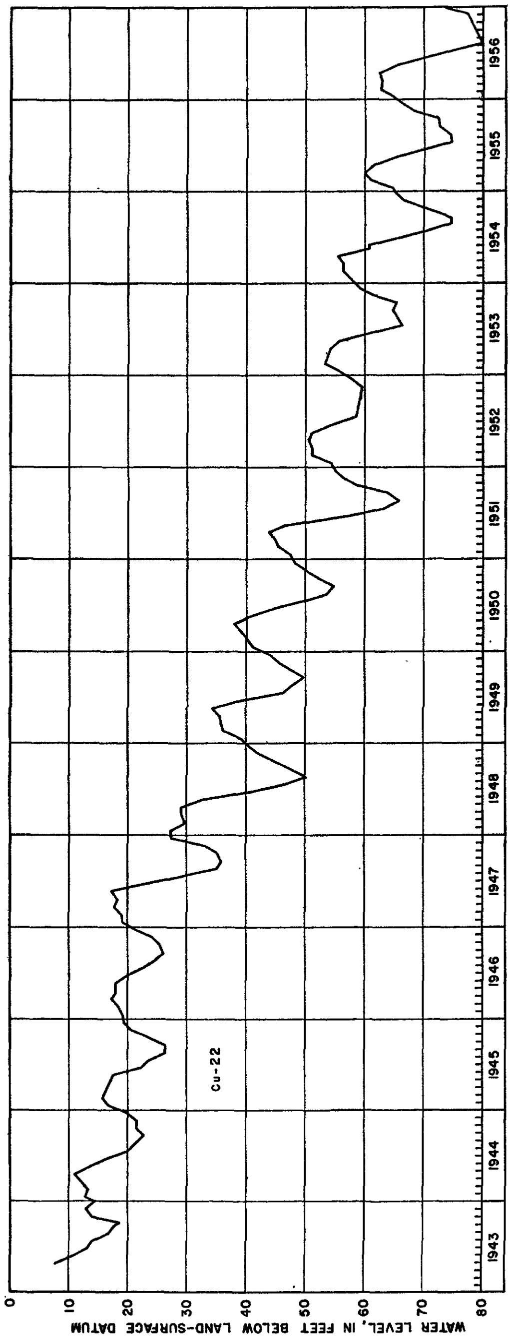

FIGURE 24.—Hydrograph of well Cu-22 screened in the "500-foot" sand in the industrial district.

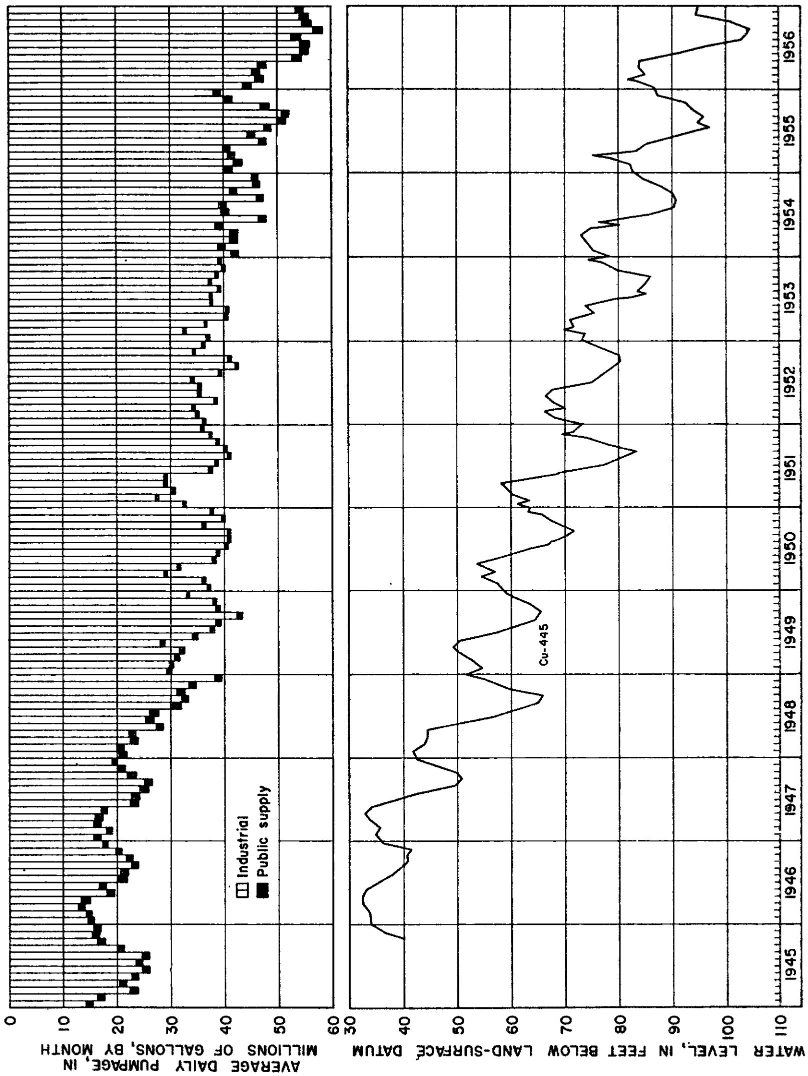

FIGURE 25.—Graph showing the relation of water levels in a well to pumpage from the "500-foot" sand in the industrial district.

lished by the Louisiana Geological Survey and the other (Jones and others, 1956) published by the U.S. Geological Survey. Maps for the period 1952–55 are included in three reports published by the Louisiana Geological Survey, Department of Conservation, and the Louisiana Department of Public Works (Fader, 1954, 1955, and 1957). Piezometric maps of the "500-foot" sand in Calcasieu Parish for the months of September 1943, October 1946, and September 1949 are included in an open-file report issued in 1950 (Jones).

A piezometric map of the "500-foot" sand was prepared for this report from water-level measurements made during September 1955. (See pl. 5.) Contour lines connecting points of equal water-surface elevation in wells used as control points show the altitude to which water rose in wells screened in the "500-foot" sand. Water-level-contour (piezometric) maps indicate, directly or indirectly, the direction of ground-water flow, areas of recharge and discharge, ground-water divides, water levels with reference to a known datum, and effects of pumping; and when used with other hydrologic data, they show the rate of movement. Moreover, by comparing successive maps, changes in ground-water storage may be computed.

The direction of flow of ground water is downgradient along flow lines—lines crossing all contours at right angles. The direction of movement of the water in the "500-foot" sand in Calcasieu Parish is toward areas of heavy pumping. This is in contrast to conditions in 1903, when there was little or no pumping and the direction of movement throughout the parish was southward (Jones and others, 1954, pl. 17).

Pumping tests on both industrial and irrigation wells were made at six separate sites. One purpose of the tests was to determine the hydraulic characteristics of the aquifer so that the effect of withdrawals of water could be predicted.

The transmissibility of an aquifer determined by pumping tests can be verified by comparing the quantity of water pumped from an area with the quantity of water moving into the area as calculated by Darcy's law and data from the piezometric map. Darcy's law is expressed as—

$$Q=PIA \qquad (2)$$

where—

Q is quantity of discharge per unit time
P is permeability
I is hydraulic gradient
A is cross-sectional area through which water percolates.

This equation can be rewritten by substitution in the following manner:

$$Q=\frac{T}{m}I(Lm)=TIL \qquad (3)$$

where—

$P=\frac{T}{m}$

T is transmissibility

A is Lm

L is length, normal to direction of flow, of the section through which the water moves

m is thickness of aquifer.

The hydraulic gradient between the contour lines is given by the formula

$$I=\frac{c}{d}=\frac{c}{B/L}=\frac{cL}{B} \tag{4}$$

where—

c is contour interval

d is average distance between contours

B is area between contours

d is $\frac{B}{L}$.

By substituting equation 4 into equation 3 the expression may be written—

$$Q=T\times\frac{cL}{B}\times L=\frac{TcL^2}{B} \tag{5}$$

where—

Q is expressed in gallons per day

T is in gallons per day per foot

c is in feet

L is in miles

B is in square miles

By use of formula 5 and data from the piezometric map, the amount of water flowing across the —60- and —70-foot contour lines (pl. 5) in the vicinity of well Cu–445 can be calculated as follows:

$$Q=\frac{190{,}000\times 10\times (13.25)^2}{18.4}=18{,}000{,}000$$ gallons per day flowing across the —70 foot contour

when—

T is average coefficient of transmissibility of the "500-foot" sand in the industrial district=190,000 gpd per ft

L is calculated length and equals $(17.75+8.75)\div 2=13.25$ miles; where the length of the —60-foot contour around well Cu–445= 17.75 miles and the length of the —70-foot contour around well Cu–445 equals 8.75 miles

B is area between the —60- and —70-foot contours and equals 18.4 square miles; where the area encompassed by the —60-foot contour equals 24.4 square miles and the area encompassed by the —70-foot contour equals 6.0 square miles

c is contour interval and equals 10 feet.

The reported total pumpage from the "500-foot" sand within this area is 20.5 mgd, which results in a difference of only 12 percent from that calculated (18.1 mgd). A similar analysis made of the amount moving across the –70-foot contour in the vicinity of well Cu–77 shows that, when the transmissibility T equals 160,000 gpd per foot (table 2), about 36 mgd flows across the –70-foot contour toward the area where about 32 mgd is being pumped from the "500-foot" sand. The difference between the actual and calculated values is 14 percent. The relatively close agreement of the amount pumped and the calculated amount moving into the areas verifies the values of transmissibility determined by pumping tests.

With a coefficient of transmissibility based on an average permeability and thickness of the "500-foot" sand in the area being considered, the amount and rate of water moving northward into the area encompassed by A, B, C, and D (pl. 5) were calculated by formulas 5 and 6 as follows:

$$Q=\frac{TcL^2}{B}=\frac{150{,}000\times10\times12^2}{46.9\times7.5\times10}=60{,}000 \text{ cu ft per day (450,000 gpd) per 1-mile length of } -40\text{-foot contour}$$

where—

L is calculated length and equals 12 miles
The length of AB (—30-foot contour) equals 14 miles
The length of CD (—40-foot contour) equals 10 miles
B is area encompassed by A, B, C, and D and equals 46.9 sq miles
c is contour interval and equals 10 feet
1 cu ft water equals 7.5 gallons
T is transmissibility and equals 150,000 gpd per foot.

The velocity or rate of movement of water northward between points C and D can be calculated as follows:

$$V=\frac{Q\text{ (quantity in cu ft per day)}}{A\text{ (effective area in sq ft)}} \tag{6}$$

thus—

$$V=\frac{60{,}000}{160{,}000}=0.38 \text{ foot per day}=0.026 \text{ mile per year}$$

where—

Q=60,000 cu ft per day per mile,
A=160,000 sq ft (assuming a porosity of 25 percent and an aquifer thickness of 120 ft, the effective area per mile through which the water moves is $120\times5{,}280\times0.25=160{,}000$ sq ft).

The average distance between the –30- and –40-foot contour lines within the area $ABCD$ is 3.9 miles. On the basis of the above-calculated velocity, it would therefore require about 150 years for the water to move this distance at the present rate of pumping.

The amount and rate of movement of ground water from the north into the area of heavy pumping was calculated in a similar manner for the area marked *EFGH* (pl. 5), as follows:

$$Q=\frac{TcL^2}{B}=\frac{300{,}000\times10\times(10.5)^2}{13\times7.5\times10}=330{,}000 \text{ cu ft per day } (2{,}500{,}000 \text{ gpd}) \text{ per 1-mile length of } -40\text{-foot contour between points } E \text{ and } F$$

and—

$$V=\frac{Q}{A}=\frac{330{,}000}{330{,}000}=1 \text{ foot per day}=0.07 \text{ mile per year}$$

where—

$$A=250\times5{,}280\times0.25.$$

At the above velocity the time required for water to move from the –30-foot contour to the –40-foot contour within the area *EFGH* would be 18 years. The calculated velocities are based on the assumption that the water moves at a uniform rate throughout the thickness of the aquifer.

Within the areas considered the rate of movement southward is about three times that of the rate of movement northward and the quantity entering the area from the north is about six times that from the south where the "500-foot" sand contains salty water.

Piezometric maps may be used to outline areas of heavy pumping and, if the altitude of the land surface is known, to determine the static water level below the land surface in any locality. For example, plate 5 shows the –80-foot contour passing near well Cu–445, where the altitude of the land surface is 12 feet. Consequently, the depth to water in wells penetrating the "500-foot" sand in the vicinity of Cu–445 was 92 feet below the land surface in September 1955. The close relationship between water levels and pumping is shown by comparing the map for September 1955 (pl. 5) with the maps for 1943, 1946, and 1949 presented by Jones (1950, figs. 4, 5, and 6). The areas in which water-level declines were most significant were central and southeastern Calcasieu Parish, which were also areas of heavy pumping. The piezometric surface in the central part of the parish in 1943 was about 25 feet below sea level, whereas in September 1955 it was 100 feet below sea level. In the southeastern part of the parish, the piezometric surface declined from 6 feet below sea level in September 1943 to 30 feet below sea level in 1955.

"700-FOOT" SAND

PUMPAGE

The first known wells in the "700-foot" sand, wells Cu–186 and Cu–431 (table 6), were completed in 1918 and are not now in use because water levels have declined below the pump settings. The original yields of the wells and the water levels were not recorded. The first known large-capacity industrial well tapping the "700-foot" sand is Cu–92 near Westlake. This well had a reported yield of 2,200 gpm and a static water level of 21 feet below land surface when drilled in 1942.

As shown in table 5, the "700-foot" sand yields about 6 mgd for municipal supplies, 12.3 mgd for industrial use, and 2.5 mgd for irrigation. In 1956 there were six municipal and eight industrial wells screened in this sand. The average municipal and industrial pumpage in the vicinity of Lake Charles has increased from 4 mgd in 1945 to 17.6 mgd in 1956, or about 300 percent. (See fig. 26.)

EFFECTS OF PUMPING

The water level in well Cu–3, in the "700-foot" sand, has declined from 12 feet below the land surface in 1940 (table 6) to 68 feet below the land surface (fig. 27) in January 1956 (the time of maximum recovery), which represents an average annual decline of 3.5 feet for the 16-year period. Well Cu–3 is in the principal public-supply well field in Lake Charles. The hydrograph of well Cu–446 (fig. 26) shows that water levels have declined in the industrial district from about 26 feet below the land surface in April 1946 to 64 feet below the land surface in April 1956, or an average of 3.8 feet per year over the 10-year period. The graph of well Cu–125 (fig. 27) shows that water levels 3 miles southwest of the industrial district have declined from 10 feet below the land surface in April 1944 to 52 feet below in April 1956, or an average annual decline of 3.5 feet per year for the 12-year period. In the rice-farming area southeast of Lake Charles, the average annual decline, based upon records for Cu–173 (fig. 27), has been 2.6 feet since 1947. Thus, the water-level records indicate a general and consistent water-level decline in the "700-foot" sand throughout the parish.

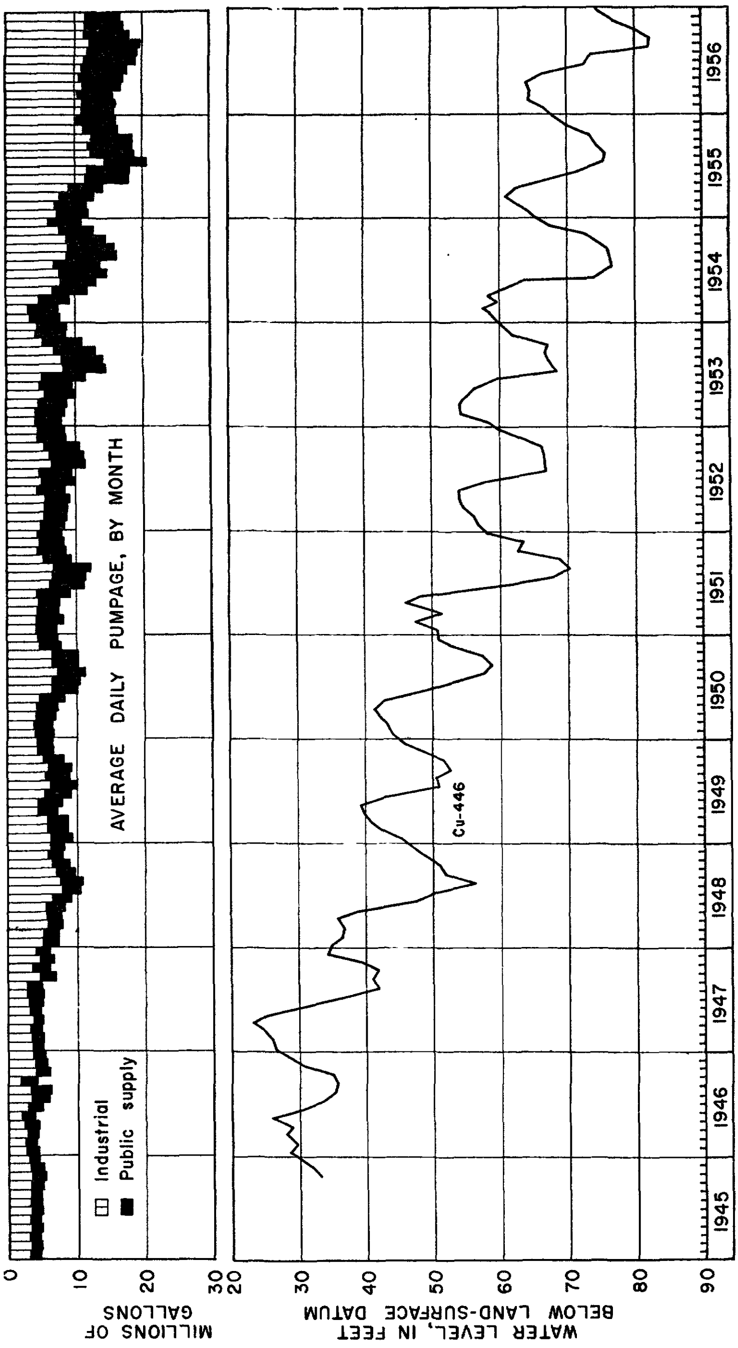

FIGURE 26.—Graph showing the relation of water levels in a well to pumpage from the "700-foot" sand in the industrial district.

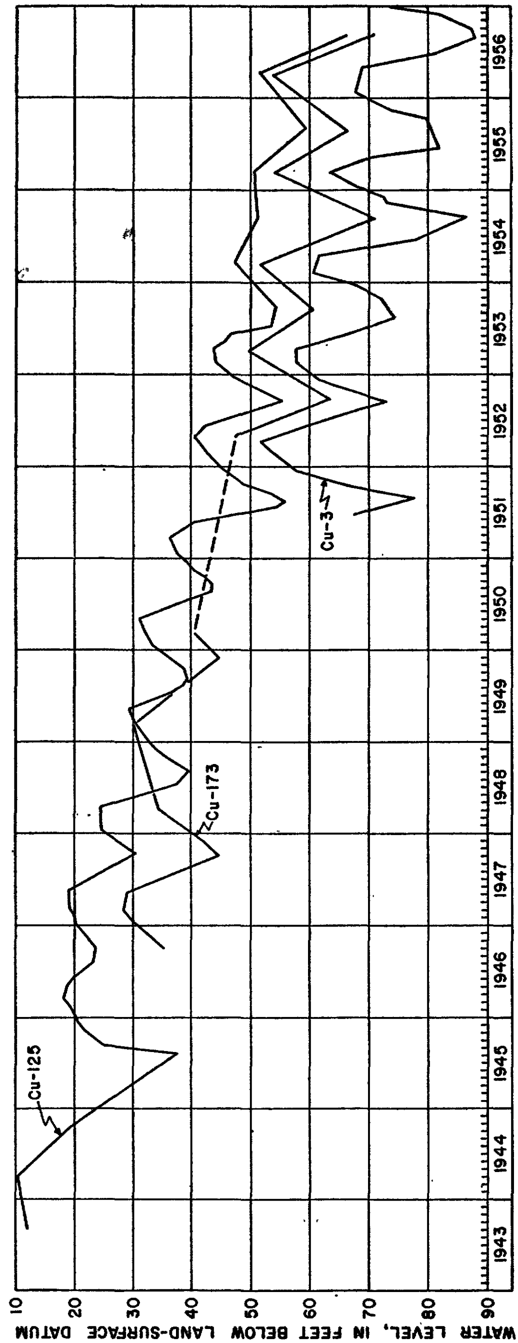

FIGURE 27.—Hydrographs of wells screened in the "700-foot" sand outside the industrial district.

DEPTH OF OCCURRENCE OF FRESH GROUND WATER

A map (plate 9) of Calcasieu Parish showing the maximum depth of occurrence of fresh ground water was prepared from data obtained from electrical logs of oil-test wells. The contour lines on the map connect points of equal altitude below mean sea level at the base of the fresh-water-bearing section. The base of this section is quite level throughout the southern and extreme eastern parts of the parish. Scattered over the entire area are mounds of salt water, which occur over some of the oil fields in the parish. At the Starks field, salt water occurs within 200–300 feet of the land surface, whereas within 2 miles around the field the depth to salt water is about 800 feet. Although the mode of occurrence of these mounds of salt water is not fully known, they may be due to upward movement of salt water along fault planes cutting fresh-water-bearing zones, displacement of salt-water-bearing beds upward so they are in contact with those containing fresh water, contamination of fresh-water-bearing sands during drilling of oil or other deep wells, or contamination of fresh-water-bearing sands by movement of salt water through defective well casings.

There is a rather abrupt increase in thickness of the fresh-water-bearing section north of the Houston River. The base of the fresh water is at a depth of 800 feet near Sulphur, 1,000 feet at the Houston River north of Sulphur, and 2,500 feet north of DeQuincy. This change in thickness of the fresh-water body probably marks the southern extent of flushing of the deeper sands by fresh ground water. Electrical logs of oil-test holes drilled in this area show fresh-water-bearing sands underlying those containing salt water. This interfingering of sands containing fresh and salt water is not fully understood but may be due to differences of head in, and permeability of, the sand beds; for example, other things being equal, the salt water would be flushed more rapidly from sands having a relatively high permeability than from those having a low permeability.

SALT-WATER ENCROACHMENT

The chloride content of water is increasing in the "200-foot" sand in the vicinity of Iowa, in the "500-foot" sand in the vicinity of the Starks oil field, and in the "700-foot" sand in the industrial district. The source of this salt water is not the overlying streams, lakes, or gulf but is within the sands themselves or the underlying or overlying sands containing salt water. Salt-water encroachment can occur by the lateral movement of saline water through a formation, vertical movement through confining materials, movement in the vicinity of salt domes and associated structural features, and leakage through defective wells.

LATERAL MOVEMENT

The sand and gravel of the aquifers in Calcasieu Parish probably were deposited in an estuarine or near-shore environment, where saline water was trapped in the aquifers. Rain falling on the exposed surfaces of the sands and gravels served to flush out the salt water. The southern extent of this flushing is dependent upon the time available since deposition of the sand and upon the rate of movement of water in the aquifer. Because the aquifers of Calcasieu Parish pinch out toward the south, the rate of movement of the water under natural conditions was probably governed by vertical seepage from the sands through overlying confining beds.

Originally the direction of movement of the water in the principal sands in Calcasieu Parish was southward and served to push the fresh water-salt water interface southward into southern Calcasieu and Cameron Parishes. Pumping has caused the hydraulic gradient to be reversed in the southern part of Calcasieu Parish, and ground water is moving northward toward areas of heavy withdrawals. Because of the lack of definitive observation wells, the exact location of the fresh water-salt water interface in the sands is not known. However, an approximation of the time required for the water to move from the southern edge of the parish toward the area of heavy pumping may be made by the method described in the report under "Analysis of piezometric maps." Under existing conditions the rate of movement is very slow, and many years would elapse before the salt-water interface could reach the industrial district.

The trend of chloride concentration in water from a large-capacity well (Cu–588) in the "500-foot" sand in the southern part of the industrial area is shown graphically in figure 28. For the past 4 years the chloride content of water from well Cu–588 and other wells in the southern part of the parish has been more or less constant, indicating that the salt water within the "500-foot" sand has not moved northward into the industrial district.

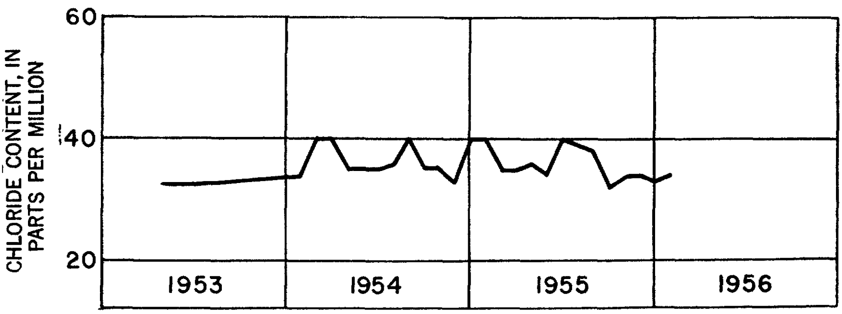

FIGURE 28.—Graph showing the chloride content of water from well Cu–588.

The chloride content of water from wells screened in the "700-foot" sand is given in table 7. Within the industrial district, the chloride content of water pumped from the "700-foot" sand has increased more rapidly than in other known areas of increasing chloride. This increase of chloride in the industrial district is shown graphically on figure 20. In well Cu-96 (736 feet deep) the chloride content increased from 285 ppm in 1945 to 450 ppm in 1951. In well Cu-98 (767 feet deep) the chloride content increased from 95 ppm in 1945 to 340 ppm in 1952. Records of the quality of water from well Cu-462 (724 feet deep) show that the chloride content increased from 20 ppm in 1949 to 215 ppm in 1955. Well Cu-96, drilled in 1943, was put on a standby basis in 1947 because of the high concentration of chloride in the water. During 1947-51 well Cu-96 was pumped only for the purpose of determining the chloride content of the water. Well Cu-98 was put into production late in 1942, was retired to standby basis in 1950 and was pumped only to obtain water for determinations of the chloride content during 1951-52. The progressive contamination of the "700-foot" sand, as shown on figure 20, indicates that local contamination is by residual salt water in the lower part of the sand or by the advance of a nearby salt-water interface as the result of pumping.

VERTICAL MOVEMENT

In an area such as Calcasieu Parish, where fresh-water-bearing sands overlie and may be separated from salt-water-bearing sands by a relatively thin clay layer, movement of salt water through clay into fresh-water-bearing sands can occur if the hydrostatic head in the fresh-water-bearing sand is less than that in the salt-water-bearing sand. A theoretical example of this type of contamination can be considered under the following assumptions: The clay underlying a fresh-water aquifer is 50 feet thick; the difference in head of the water contained in the two aquifers is 10 feet; and the permeability of the clay is 0.2 gpd per square foot (Wenzel, 1942, p. 13). Then from formula (2)

$$Q=PIA$$

$$=\frac{0.2\times 10\times 1\times (5{,}280)^2}{50}=1{,}100{,}000 \text{ gallons per day per square mile.}$$

Although no permeability measurements of clay have been made in Calcasieu Parish, the above example clearly shows that, considering the areas involved, significant amounts of water can move through a relatively thick clay bed. As indicated by the increasing chloride content of the water, there may be contamination of the "700-foot" sand by underlying salt-water-bearing sands in the vicinity of the Lockport and Sulphur Mines oil fields.

Another way in which salt water can enter fresh-water aquifers is by downward movement of saline water from shallow sands into the deeper fresh-water-bearing sands. In Calcasieu Parish, water from well Cu–562, which is 22 feet deep, has a chloride content of 1,320 ppm (table 7). Because of the higher water level in the shallow sand, this saline water could migrate to deeper fresh-water-bearing sands. Sufficient data to indicate conclusively whether this type of contamination is occurring in Calcasieu Parish are lacking.

MOVEMENT IN VICINITY OF STRUCTURES

The contamination of fresh-water-bearing sands by movement of salt water upward through the disturbed sedimentary rocks overlying salt domes has been suggested as an explanation of the salt-water mounds (pl. 9) overlying many oil fields in Calcasieu Parish. However, Winslow and Doyle (1954, p. 30) suggest that "some of the apparent contamination may be the result of a lack of circulation rather than actual contamination from the salt or underlying salt-water sands." At the Starks dome, water from wells Cu–613 (85 feet deep) and Cu–585 (483 feet deep) had concentrations of chloride of 430 ppm and 907 ppm, respectively. No hydrologic boundaries that might indicate the presence of faulting in this area were determined during the pumping test made on these and other wells. For this reason, contamination of the shallow sands by the movement of saline water along fault planes is not considered to have been effective in this area.

DEFECTIVE WELLS

Fresh-water-bearing sands can be contaminated by the movement of salt water through defective wells. Wells having leaky casings may serve as effective conduits for the passage of salt water into sands containing fresh water. This means of contamination has been described in reports on other areas (Thompson, 1928, p. 98–107; Sayre, 1937, p. 77; Bennett and Meyer, 1952, p. 158–173; Piper and others, 1953). Although such contamination has not been proved in Calcasieu Parish, it may occur to some degree in abandoned oil and sulfur wells.

CORRECTIVE MEASURES

It will be necessary to continue the collection of data on the location of salt water in Calcasieu Parish to determine the sources of local contamination. After the sources are determined it may be possible to inaugurate corrective measures to prevent the spread of contamination. Such measures may include protective pumping, the repair of leaky casings, control of discharge of water from wells, or other methods designed to meet specific problems.

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WELL CONSTRUCTION AND METHODS OF LIFT

EXPLORATORY METHODS

Generally when a well or well field is to be installed, test holes should be drilled to determine the occurrence of the fresh-water-bearing sands. During drilling, an accurate record should be made of the beds penetrated, the drilling time required, and formation samples collected. After the test hole has been drilled to the specified depth, it is desirable to make an electrical log for correlation purposes and to determine the occurrence of sands containing fresh water. If the data collected from the test hole indicate favorable conditions, the hole is reamed to the desired diameter, and the supply well installed.

The electrical log is a record of the potential and resistivity of the formations penetrated by the well bore. The spontaneous-potential curve (in millivolts) is generally shown as a single trace on the left side of the conventional commercial electrical log, and the resistivity curves, on the right side. In the gulf coast area, of which Calcasieu Parish is a part, the spontaneous-potential curve generally has a positive deflection opposite fresh-water-bearing sands and a relatively large negative deflection opposite salt-water-bearing sands. In Calcasieu Parish the resistivity reading (measured in $\frac{\text{ohm m}^2}{\text{m}}$) generally is high opposite sands containing fresh water and low (less than $20\frac{\text{ohm m}^2}{\text{m}}$) opposite salt-water-bearing sands and shales. This selection of 20 ohms for determining fresh-water-bearing sands from electrical logs is based upon a correlation of resistivity readings from logs and quality-of-water data in southwestern Louisiana.

A drill-stem test may be made if it is necessary to determine precisely the quality of water. A short length of screen is attached to the drill stem and is set opposite the sand to be tested. To prevent contamination of the water, packers are usually set above and, if needed, below the section being tested. After an adequate water sample is collected, the drill stem and screen are removed from the hole. Drill-stem testing may be used also to obtain water-level measurements and data on the potential yield of a supply well.

CONSTRUCTION

All the industrial, municipal, and irrigation wells, and most of the rural supply wells in Calcasieu Parish have been drilled by the hydraulic-rotary method. The drilling is done by rotating a bit on the end of a drill-stem pipe which is screwed onto the kelly, a section of drill pipe, either square or ribbed that fits into the drive bushing in the rotary table on the derrick floor. A mud fluid, sufficiently viscous to seal up the walls of the hole and to carry the cuttings to the surface, is pumped, under pressure, down the drill pipe and out through holes in the bit. Jetted against the bottom of the well with high velocity, the fluid is deflected upward to the surface between the drill pipe and walls of the hole carrying the drill cuttings.

Another recently developed method used in some areas of Louisiana for drilling water wells is the reverse-rotary method. In this method clear water flows from a pit on the surface down the annular space between the drill pipe and walls of the hole. The cuttings and water are returned in an ascending stream through the drill-stem pipe to the clear-water pit. A large pit and source of clear water are needed to replace water dissipated in permeable zones and to maintain a relatively constant head to prevent loss of circulation. After drilling is completed it is necessary that this head be maintained until the casing and screen are set. The principal advantage of the reverse-rotary method is that clear water is used for drilling and consequently the water-bearing material near the bore hole is not clogged with drilling mud. For this reason the well generally can be developed in a shorter period of time. However, most of the reverse-rotary rigs presently (1956) in use reportedly have not been used to drill below a depth of about 600 feet. It has been reported that newer techniques and developments will allow reverse-rotary drilling to greater depths.

The principal components of a typical industrial or irrigation well and its pumping equipment are shown in figure 29. The purpose of the pit casing is to provide ample space for installation and submersion of the pump. Where water levels are declining, as they are in Calcasieu Parish, care should be taken to set a sufficient length of pit casing so that the pump bowls will be deep enough to prevent loss of suction. When the pumping level declines below the pump bowls, the quantity of water delivered decreases rapidly until the pump breaks suction. If the pump bowls are set at the bottom of the pit casing and the water levels decline below the limit of suction lift, it is necessary either to install a smaller pump with less capacity in the well casing below the bottom of the pit casing or to construct a new well.

In Calcasieu Parish there are two general types of wells: a gravel-pack well made by reaming the hole to a large diameter (as much as 28 to 32 inches) in the sand to be screened, and placing sized gravel around the screen; and the so-called natural-pack well in which the screen is set opposite the sand without introduction of gravel. In natural-pack wells the size of the openings in the screen is such that the finer grained 40 to 70 percent of the sand grains,

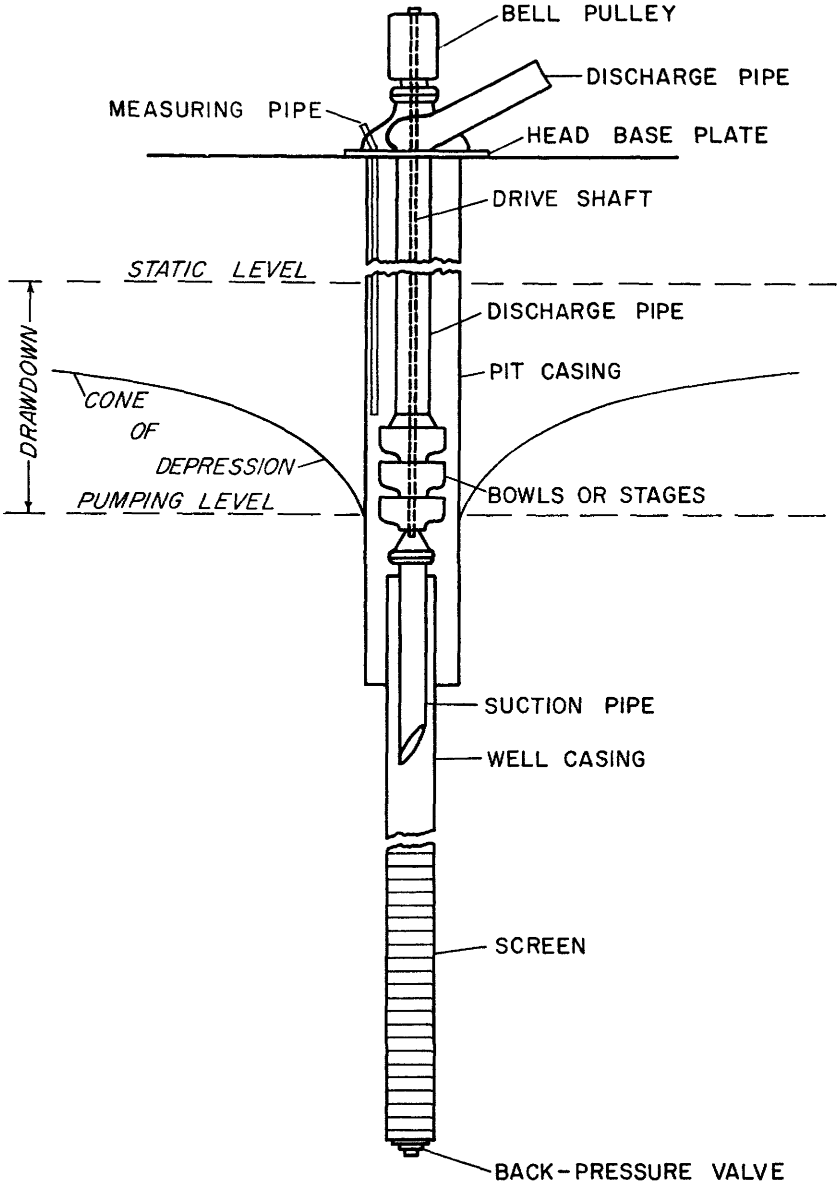

FIGURE 29.—Typical irrigation well.

as shown by the mechanical analysis, will pass through the screen and into the well. In irrigation wells the finer grained 90 percent of the sand grains is allowed to pass through the screen.

The well is developed by backwashing, surging, crosswashing, or overpumping, or by a combination of these processes. For maximum well efficiency, development should continue until the specific capacity no longer increases with increased yield. Development generally is continued until a yield is obtained that is greater than that of the permanent pump but less than the critical discharge. (See fig. 7.) This is based on the theory that the velocity of water toward the screen during normal operation will be less than that incurred during the development of the well and thus there will be no transportation of fine sand toward and through the screen of the completed well.

METHODS OF LIFT

The size and type of pump used depend principally upon the pumping lift (distance from land surface to water level in the well being pumped), the quantity of water desired, the external head, and the diameter of the pit casing. In turn, the type and power of the engine used to operate the pump are determined by the capacity and speed of rotation of the pump and by the total lift. Rural supply wells in the shallow sands are usually equipped with pitcher pumps, and rural wells in the principal sands of the Chicot aquifer are equipped with small-capacity deep-well turbine or jet pumps. All public-supply, industrial, and rice-irrigation wells have deep-well turbine pumps of capacities dependent upon the needs of the user. With few exceptions, rural, public-supply, and industrial wells in Calcasieu Parish are powered by electricity. Of 76 inventoried rice-irrigation wells, 26 were equipped with diesel or semidiesel engines, 6 with natural-gas engines, 4 with electric motors, and 4 with butane-gas engines. The type of power used to operate 36 irrigation wells was not recorded.

SUMMARY AND CONCLUSIONS

The rocks of Calcasieu Parish that contain fresh water range in age from Recent to Miocene. No water wells have been drilled to the fresh-water-bearing sands of Pliocene and Miocene ages; however, records of wells in adjoining parishes indicate that moderate supplies of soft water are available from these beds. Small supplies, generally for domestic purposes, are available from shallow sands of Recent and Pleistocene ages. The principal aquifer (Chicot) in Calcasieu Parish consists of the "200-foot," "500-foot," and "700-foot" sands of Pleistocene age. In 1955 about 105 mgd of ground water was pumped in Calcasieu Parish. About 11 percent was from the "200-foot" sand, 66 percent from the "500-foot" sand, and 20 percent from the "700-foot" sand.

The principal users of this water are the many industries in the parish, rice irrigators, and the city of Lake Charles. Of the 105 mgd used in 1955, 62 percent was for industrial use, 26 percent for irrigation, 8 percent for municipal supplies, and 4 percent for rural use.

The "200-foot" sand is generally thin in the western half of the parish; however, in the vicinity of Lake Charles and in the eastern half of the parish, it is quite thick and wells have an average yield of 2,800 gpm. Coefficients of transmissibility and storage are about 260,000 gpd per foot and 0.00086, respectively, in the southeastern part of the parish. The decline of water levels in the "200-foot" sand has been relatively small throughout the parish as a whole, averaging about 2 feet per year since 1946. The quality and temperature of the water make it a suitable source of supply for most purposes. This aquifer is a potential source of large additional amounts of water in the southeastern and central parts of the parish.

The "500-foot" sand is the most highly developed aquifer in the parish. This sand is a thick (as much as 310 feet), continuous unit throughout most of the parish, but it becomes thinner (25 feet) in the southeastern part of the parish. Yields from large-diameter wells screened in this sand range from about 1,300 to 4,000 gpm. Pumping tests made at various sites indicate the coefficient of permeability to range from 1,000 to 2,000 gpd per square foot. The water-level map (pl. 5) and the values of the coefficients of transmissibility and storage determined from pumping tests indicate that the water in the "500-foot" sand is moving southward at a greater rate than it moves northward into the indistrial district. Static water levels have declined at a rate of about 5 feet per year at well Cu–445 in the industrial district. Although the present decline of water levels in the areas of heavy pumping is relatively large, as compared to the other sands, it is not excessive and must be expected in order to provide a gradient sufficient to move the required amount of water into the areas of pumping. A wider spacing of wells, as new ones are drilled to replace old wells, would minimize interference between them.

Except in small areas, there is no increase in the chloride content of the water in the "500-foot" sand as a result of the present withdrawals. The iron content of the water varies considerably, ranging from about 0.06 ppm to 11 ppm. However, areas of high iron content appear to be of only small extent. The temperature of water in the "500-foot" sand averages 74°F. On the basis of this study, it is concluded that the "500-foot" sand is capable of supplying additional amounts of water without any appreciable change in the quality of the water.

The "700-foot" sand is present throughout the parish and is capable of yielding large amounts of water. In some areas it contains small interbedded layers of clay, but the sands are considered to be hydrologically connected. Within the industrial district this aquifer has an average thickness of 220 feet. Original yields of industrial wells screened in this sand average about 1,500 gpm. Because less water is pumped from this deeper sand, water levels have declined less and are generally higher than in the overlying "500-foot" sand. In the industrial district, at well Cu–446, the water level has declined from about 26 feet in April 1946 to 64 feet in April 1956, or about 3.8 feet per year. The water level in well Cu–3, a municipal-supply well, has declined at a rate of about 3.5 feet per year. The principal factor limiting development of this sand is the relatively high chloride content of the water in the central and southern parts of the parish. The temperature of the water ranges from 74° to 78°F.

Lowering of water levels and contamination by salt water are two of the principal problems in Calcasieu Parish. To prevent excessive lowering of ground-water levels, it is necessary that new wells be drilled as far from existing well fields as economically feasible. A wider spacing of wells will result in smaller declines of water levels in the well field and a concomitant saving of pumping costs. Salt-water contamination of the "700-foot" sand has caused the abandonment of several wells in some parts of the industrial district. Adequate data are not available to determine the mode of contamination accurately; however, widespread contamination does not appear imminent. As the source of contamination in each well or well field is determined, it may be possible to establish corrective measures to prevent the spread of salt water to nearby wells.

Because ground-water conditions in Calcasieu Parish are not static but change with time and development of ground water in the area, a program to collect and analyze current information should be continued. The principal phases of the program should include collection of well records, a continuing inventory of water use and measurement of water-level fluctuations, periodic sampling of water in selected wells to determine the status of salt-water encroachment, and detailed studies of the effect of geologic structural features on the occurrence and contamination of ground water.

DESCRIPTION OF WELLS

The records of wells in table 6 are based on information obtained from many sources and are of different degrees of completeness and accuracy. The wells are located as accurately as possible, but many of the old wells in Calcasieu Parish are no longer visible and can be located only approximately. Wells for which records are incomplete or for which the location cannot be approximated within a reasonable distance are not included.

TABLE 6.—*Description of*

Type of well: B, bored;
Use of water: A, abandoned; D, domestic; I, industrial; Ir,
Remarks: L, driller's log in table 8; C, chemical

Well	Owner	Owner No.	Location			Date completed	Type of well	Depth of well (feet)	Casing	
									Pit	
			Sec.	T.S.	R.W.				Length (feet)	Diameter (inches)
Cu- 1	Town of Vinton		15	10	12	1939	Dr	585	536	8
2	do		15	10	12		Dr	422		
3	Greater Lake Charles Water Co.	H	31	9	8	1940	Dr	700		18
5	J. Turner		8	8	8		Dr	430		
6	Central La. Electric Co.		18	7	10	1940	Dr	654		
7	Calcasieu Parish School Board.		35	8	13	1929	Dr	601		
8	Krause and Managan		15	9	9	1895	Dr	500		
9	L. C. Managan		35	9	9	1938	Dr	178		
10	Krause and Managan		26	9	9	1940	Dr	193		
11	L. C. Managan		35	9	9	1942	Dr	475	85	4
12	Magnolia Petroleum Co.		4	10	9	1924	Dr	456		6
13	do		4	10	9	1925	Dr	716	52	12
14	do		4	10	9		Dr	796	85	16
15	do		9	10	9		Dr	500±		13
16	do		30	10	9	1938	Dr	328		
17	Cities Service Refining Corp.		24	10	10		Dr	500		
18	W. T. Burton		20	10	9	1933	Dr	330		
19	Bell Estate		10	10	10	1938	Dr	488		7
20	Magnolia Petroleum Co.		4	10	9		Dr	290		
21	Continental Oil Co.		8	10	9		Dr	265		
22	Magnolia Petroleum Co.		8	10	9	1935	Dr	560		13
23	Continental Oil Co.		8	10	9	1938	Dr	251		
25	Lake Charles Golf Club.		22	10	9	1920	Dr	500±		
27	Calcasieu Parish School Board.		26	9	9	1942	Dr	497		
28	Frank and Bob's Club		4	10	8		Dr	447		
29	Mr. Hinton		8	10	9	1942	Dr	442		
31	Greater Lake Charles Water Co.	K	31	9	8	1942	Dr	696		18
32	H. Hart		26	9	9	1942	Dr	198		4
33	Greater Lake Charles Water Co.	G	31	9	8	1925	Dr	500		12
34	do	A	31	9	8	1942	Dr	700		
35	do	F	31	9	8		Dr	500		
36	do	B	31	9	8		Dr	700		
37	do	C	31	9	8		Dr	700		
38	do	D	31	9	8		Dr	700		
40	Hardwood Lumber Co.		21	9	8	1942	Dr	400		6
41	do		21	9	8		Dr	400		6
42	Bell Estate		29	9	8	1925	Dr	504		
43	Halliburton Oil Well Cementing Co.		4	10	8	1937	Dr	500		
44	Calcasieu Parish School Board.		28	9	8	1940	Dr	430		
45	J. Verret		18	10	8		Dr	224		4
46	Missouri Pacific RR.		9	10	8	1942	Dr	564		8
47	do		9	10	8	1910	Dr	575		7
48	Calcasieu Parish School Board.		18	10	8		Dr	500		
49	G. Boling		18	10	8	1939	Dr	195		
50	McNeese State College.		19	10	8	1890	Dr	600±		
51	McCalls Dairy		20	10	8	1936	Dr	220		
53	Charles Sigler		34	9	9		Dr	200		
62	Charles Fay		22	10	9	1936	Dr	507		

wells in Calcasieu Parish, La.

Dr, drilled; Du, dug.
irrigation; N, none; O, observation; P, public; S, stock; T, test
analysis for water collected in well in table 7

Casing: Well: Length (feet)	Casing: Well: Diameter (inches)	Screened interval (feet)	Aquifer	Static water level below or above (+) land-surface datum: Feet	Static water level below or above (+) land-surface datum: Date	Yield (gpm)	Use of water	Remarks
45	6	536–585	"500-ft"	0.5	June 1940		P	C.
	6		"500-ft"	.7	do		A	
			"700-ft"	12 87	1940 September 1956	1,340	P	C.
	6		"500-ft"	8	August 1940		A	
580	12	580–654	"700-ft"	82	do	360	P	L. Specific capacity 5 gpm per ft.
	4		"700-ft"	1	do		P	C.
	8		"500-ft"				A	Flowed until 1936.
	2½		"200-ft"	7	1938		A	
	2½		"200-ft"	+13	November 1940		A	
	3½		"500-ft"	21	July 1942		P	
	4	414–456	"500-ft"	49 57	February 1950 September 1956		I	
	6	675–716	"700-ft"	11	January 1943		A	
	8	668–765	"700-ft"	19	do		A	
	4		"500-ft"	8	do		A	
	4		"500-ft"	19	do		A	
	4		"500-ft"	17	do		A	
	4		"500-ft"	28	do		A	Flowed in 1933.
	4		"500-ft"	5	do		A	
	6		"500-ft"	55 46	1940 August 1946		N	
	4		"200-ft"	26 47	January 1943 March 1952		A	
	7	520–560	"500-ft"	8 81	April 1943 September 1956		O	L. Flowed in 1935.
	6		"200-ft"	25	January 1943		A	
	4		"500-ft"	9	do		A	Flowed until 1938.
	4	490–497	"500-ft"	21	November 1942		P	
	2½		"500-ft"	9	January 1943		A	
	2½		"500-ft"	26	1942		D	
	10		"700-ft"	12	do	1,650	P	C.
	2½		"200-ft"	66	November 1942		D	
	6		"500-ft"	11 68	January 1943 November 1955		P	L. Rescreened in 1935 in the "500-ft" sand only.
	8		"700-ft"	12 48	1942 June 1951		A	
	6		"500-ft"				P	
	8		"700-ft"				A	
	8		"700-ft"				A	
	8		"700-ft"				A	
	4		"500-ft"	15	June 1942		I	
	3		"500-ft"	13	April 1943		A	
	6		"500-ft"	10 37	January 1943 September 1947		A	Flowed when completed.
	3		"500-ft"	10	January 1943		A	
	4		"500-ft"	12	1940		P	
	2½		"200-ft"	27 53	January 1943 March 1956		O	
	6	525–564	"500-ft"	13	April 1942		I	L.
	4		"500-ft"	14 25	January 1943 October 1946		A	
	3		"500-ft"	22 37	January 1943 August 1949		A	
	2½		"200-ft"	24	January 1943		A	
	4		"500-ft"	8 10	do October 1948		A	
	4		"200-ft"	20	January 1943		I	
	2½		"200-ft"				D	
	3		"500-ft"	20	1940		D	

TABLE 6.—*Description of wells in*

Well	Owner	Owner No.	Location Sec.	Location T.S.	Location R.W.	Date completed	Type of well	Depth of well (feet)	Casing Pit Length (feet)	Casing Pit Diameter (inches)
Cu-65	G. Collins		22	9	8	1942	Dr	400		
71	Home Ideal Laundry		31	9	8	1940	Dr	463		
73	W. Williamson		4	9	8	1935	Dr	210		
74	Firestone Tire & Rubber Co.		18	10	9	1942	Dr	545		18
75	do		18	10	9	1943	Dr	752		18
76	do		18	10	9	1943	Dr	527		18
77	Olin Mathieson Chemical Corp.		35	9	9	1943	Dr	512		10
78	do	1	34	9	9	1934	Dr	513		16
79	do	2	34	9	9	1934	Dr	519		20
80	do	4	35	9	9	1940	Dr	517		24
81	do	3	35	9	9	1940	Dr	525		18
82	do	5	34	9	9	1942	Dr	517		18
83	do	6	35	9	9	1943	Dr	505		18
84	Lake Charles Harbor and Terminal District.		2	10	9	1926	Dr	677		16
85	do		2	10	9	1937	Dr	503		12
86	Continental Oil Co.	1	34	9	9	1940	Dr	529		18
87	do	2	34	9	9	1940	Dr	236		24
88	do	3	27	9	9	1940	Dr	275		24
89	do	4	27	9	9	1940	Dr	520		18
90	do	5	27	9	9	1940	Dr	255		24
91	do	6	27	9	9	1940	Dr	526		18
92	do	7	34	9	9	1942	Dr	701		18
93	Cities Service Ref. Corp.	J-2	19	10	9	1943	Dr	521	402	18
94	do	J-2B	19	10	9	1943	Dr	520	399	18
95	do	J-2A	19	10	9	1942	Dr	527	399	18
96	Petroleum Chemicals, Inc.	1	18	10	9	1943	Dr	736	612	18
97	do	2	18	10	9	1943	Dr	519		18
98	do	3	18	10	9	1942	Dr	767		18
99	Columbia-Southern Chemical Corp.	1	3	10	9	1942	Dr	667		18
100	do	2	4	10	9	1942	Dr	685		18
101	do	3	3	10	9	1942	Dr	670		18
102	Union Oil and Gas Co.		29	9	10		Dr	575		
103	do		29	9	10		Dr	575		
104	do		29	9	10		Dr	575		
105	S. Hunter		21	9	11		Dr	480		
106	S. A. Emerson Oil Corp.		21	9	11		Dr	650		
108	Union Oil of California		33	10	12		Dr	668		
110	Central La. Electric Co., Inc.		18	7	10	1927	Dr	172		
111	do		18	7	10		Dr	300		
112	I. V. Maurer		25	9	9		Dr	210		4
114	F. P. Friesen		29	11	8	1942	Dr	700		18
115	Krause and Managan		11	9	10		Dr	348		

Calcasieu Parish, La.—Continued

Casing: Well: Length (feet)	Casing: Well: Diameter (inches)	Screened interval (feet)	Aquifer	Static water level below or above (+) land-surface datum: Feet	Static water level below or above (+) land-surface datum: Date	Yield (gpm)	Use of water	Remarks
	2½		"500-ft"	8 13	1942 April 1943		D	
	4	451–463	"500-ft"				I	C.
190	2½	190–210	"200-ft"	20	July 1943		D	
	10	415–545	"500-ft"	11	November 1943	1,500	I	L. Specific capacity 42 gpm per ft.
	10	658–752	"700-ft"	10	March 1943	1,500	A	L. Specific capacity 15 gpm per ft.
	10	397–527	"500-ft"	7	January 1943	1,500	I	Specific capacity 47 gpm per ft.
	6	448–512	"500-ft"	31 121	June 1943 August 1956	1,500	O	
	10	433–513	"500-ft"	99	October 1950	1,500	I	C. Specific capacity 31 gpm per ft.
	12	399–519	"500-ft"	46	October 1945	1,500	I	Flowed when completed.
	16	437–517	"500-ft"	+2 90	March 1940 October 1950	1,500	I	Specific capacity 75 gpm per ft.
	10	435–525	"500-ft"	5 108	March 1940 October 1950	1,500	I	Specific capacity 39 gpm per ft in 1950.
	10	429–517	"500-ft"	41 69	October 1945 September 1954	1,500	A	
	10	442–505	"500-ft"	30	July 1942	1,500	I	C. Specific capacity 31 gpm per ft.
	6		"700-ft"	52 62	October 1949 June 1951		A	C.
	8	443–503	"500-ft"			1,350	I	
	10	429–529	"500-ft"	8	September 1940	2,000	I	C.
	12	156–236	"200-ft"	12	July 1940	2,000	A	
	12	195–275	"200-ft"	5	do	2,000	I	
	10	420–520	"500-ft"	5	August 1940	2,000	I	
	12	185–255	"200-ft"	8	September 1940	2,000	I	C. Specific capacity 50 gpm per ft.
	10		"500-ft"	7	July 1940	2,000	I	C.
	12	623–701	"700-ft"	21	July 1942	2,200	I	C.
68	10	408–521	"500-ft"	13	February 1943	2,000	I	
87	10	413–520	"500-ft"	12 48	January 1943 March 1948	2,000	I	
91	10	417–527	"500-ft"	12 42	November 1942 June 1944	2,000	I	Specific capacity 32 gpm per ft.
63	10	641–736	"700-ft"	12 40	October 1942 August 1945	2,000	N	L. Specific capacity 37 gpm per ft.
	10	410–519	"500-ft"	12 115	October 1942 September 1956	2,000	I	C. Specific capacity 26 gpm per ft.
	10	629–767	"700-ft"	12 33	December 1942 June 1945	2,000	N	L, C. Specific capacity 30 gpm per ft in 1945.
	12	562–646	"700-ft"	12 87	May 1942 December 1951	1,500	I	L, C. Specific capacity 17 gpm per ft.
	10	589–685	"700-ft"	11	April 1942	1,500	I	C. Test hole drilled to 852 ft.
	10	572–670	"700-ft"	12	do	1,500	A	Specific capacity 71 gpm per ft.
	10		"500-ft"	7	August 1943		A	
	10		"500-ft"			100	I	
	10		"500-ft"			100	I	
	6		"500-ft"	6	November 1943		A	
	4		"700-ft"				A	
	6	648–668	"700-ft"				I	L, C.
			"200-ft"				A	
			"500-ft"				A	
	2½		"200-ft"	51	August 1943		A	L.
	10		"500-ft"	41	April 1956	2,000	Ir	L.
	4		"500-ft"	3 21	September 1943 September 1956		O	

TABLE 6.—*Description of wells in*

Well	Owner	Owner No.	Location Sec.	Location T.S.	Location R.W.	Date completed	Type of well	Depth of well (feet)	Casing Pit Length (feet)	Casing Pit Diameter (inches)
Cu-117	Union Sulphur Co.		10	9	10		Dr	500±		24
118	City of Sulphur		34	9	10	1929	Dr	510		
119	do		34	9	10	1936	Dr	497		10
120	Olin Mathieson Chemical Corp.		36	11	10	1933	Dr	700±		
122	Calcasieu Marine Bank.		22	11	10		Dr	723		
124	E. J. Stein		18	11	10		Dr	700±		24
125	C. Patterson		34	10	10		Dr	700		24
126	Swift Packing Co.		1	10	8	1937	Dr	510		12
127	do		1	10	8	1942	Dr	517		12
128	S. Alford		25	9	8	1939	Dr	418		4
130	H. Huber		31	9	6		Dr	360		
133	Shell Oil Co.		13	9	7	1932	Dr	291		9
134	do		13	9	7	1933	Dr	261		9
135	do		6	11	9	1933	Dr	526		
136	do		23	9	7	1933	Dr	243		
137	do		30	9	6	1933	Dr	306		7
138	Magnolia Petroleum Co.		12	9	7		Dr	297		9
144	M. Chatagnier		32	9	6	1943	Dr	312		
145	B. Pelican		32	9	6		Dr	348		
146	B. Pugh		17	10	6		Dr	350		24
147	J. Metzger		18	10	6	1920	Dr	359		24
148	do		18	10	6	1942	Dr	366		20
150	E. Daughenbaugh		31	10	7	1918	Dr	667		24
151	do		29	10	7	1943	Dr	860	99	18
153	do		7	11	5		Dr	400±		
156	O. Primo		35	10	7	1917	Dr	454		24
157	U.S. Air Force		9	11	7		Dr	232		
158	R. Gregg		30	11	6		Dr	440		24
159	E. Fruge		25	11	7	1938	Dr	424		24
160	J. Demarest		35	11	7		Dr	387		24
161	Calcasieu Marine Bank.		26	11	7		Dr	450		24
162	Stanolind Oil and Gas Co.		4	11	7	1917	Dr	700		24
163	do		5	11	7	1917	Dr	700		24
164	S. Vallet		13	11	8	1943	Dr	359		18
165	W. Helm		29	11	7	1943	Dr	386		18
166	F. Helm		17	11	7		Dr	388		24
167	L. Wittler		35	11	8	1943	Dr	350		18
168	A. Gayle		26	11	8		Dr	375		24
169	do		1	11	8		Dr	376		18
171	do		1	11	8		Dr	375		24
172	E. Cobena		2	11	8	1943	Dr	630		18
173	Charles Linkswiler		26	10	8	1926	Dr	726		24
177	R. Peyton		27	10	8	1938	Dr	557		18
179	I. Smith		21	10	8	1911	Dr	550		24
181	C. Hoffpauir		28	10	8		Dr	805		24
182	Calcasieu National Bank.		29	10	8		Dr	600		18
186	V. M. Jones		35	9	8	1918	Dr	636		24
203	F. Weber		29	8	8	1938	Dr	393		
204	Calcasieu Parish School Bd.		9	8	8	1931	Dr	428		
205	P. Bellon		22	8	8		Dr	354		18
206	F. Gibson		26	8	8		Dr	340		18
208	W. Caldwell		6	8	8	1942	Dr	455	90	20
209	J. Tucker		14	9	9	1937	Dr	200		

Calcasieu Parish, La.—Continued

Casing: Well: Length (feet)	Casing: Well: Diameter (inches)	Screened interval (feet)	Aquifer	Static water level below or above (+) land-surface datum: Feet	Static water level below or above (+) land-surface datum: Date	Yield (gpm)	Use of water	Remarks
	12		"500-ft"	11 23	August 1943 January 1955		A	
	10		"500-ft"				P	C.
	6		"500-ft"	1	February 1936	325	P	C.
	4		"500-ft"	4 46	August 1943 September 1956		O	C. Flowed in 1942.
	10		"500-ft"				Ir	
	12		"500-ft"				A	
	12		"700-ft"	8 66	August 1943 September 1956		D	
	8	430–510	"500-ft"	9	June 1937		I	L.
	8	437–517	"500-ft"				I	C.
	2½		"500-ft"	17	September 1943		D	
	4		"200-ft"	32	April 1952		D	C.
	6	251–291	"200-ft"	24	September 1943	100	I	Specific capacity 20 gpm per ft.
	7	228–261	"200-ft"				I	
	6	496–526	"500-ft"				I	L.
	6	222–243	"200-ft"				I	L.
	6	284–306	"200-ft"				P	L.
	6		"200-ft"				I	
	10	228–312	"200-ft"			2,500	Ir	C.
	12	268–348	"200-ft"				Ir	
	12		"200-ft"	43	April 1956		Ir	C.
	10		"200-ft"	9	September 1943		A	L.
	10	274–366	"200-ft"	36	January 1950		Ir	
	12		"500-ft"	20	September 1943		Ir	
661	10	760–860	"700-ft"	29 55	do April 1956		Ir	C.
	4		"200-ft"				P	
	10		"200-ft"	23	1943		Ir	L.
	6		"200-ft"				A	C.
	12		"200-ft"	41	September 1956		Ir	
	10		"200-ft"	14	September 1943	2,850	Ir	L.
	12		"200-ft"				Ir	
	12		"200-ft"	10 36	April 1944 September 1956		O	C.
	10		"500-ft"				Ir	
	10		"500-ft"	16	September 1943		Ir	C.
	10	257–359	"200-ft"	14 59	do September 1956	2,800	Ir	
	10	288–386	"200-ft"	21 60	September 1943 September 1950	3,000	Ir	L.
	10	298–388	"200-ft"	27	September 1943	2,700	Ir	
	10	250–350	"200-ft"	14 51	do September 1956		Ir	
	12		"200-ft"	15 45	September 1943 August 1955		Ir	
	10		"200-ft"	16	September 1943		Ir	
	12		"200-ft"	17	do		Ir	
	10	543–630	"500-ft"	20	September 1943		Ir	L, C.
	12		"700-ft"	29 71	do September 1956		Ir	L, C.
	10		"500-ft"	28 50	September 1943 September 1956		Ir	
	12		"500-ft"	28	September 1943		Ir	
	12		"700-ft"	27	do		Ir	
	10		"500-ft"				Ir	
	10	498–636	"700-ft"	8	1942		A	L. Flowed until 1938.
			"200-ft"	9	1938		D	
	4		"500-ft"				P	
	8	293–354	"500-ft"	20 30	October 1943 December 1949		A	C.
	10	280–340	"500-ft"	19	October 1943	1,500	Ir	
294	10	375–455	"500-ft"	21 49	do September 1956	2,800	Ir	L, C.
	3		"200-ft"	46	January 1947		A	C.

TABLE 6.—*Description of wells in*

Well	Owner	Owner No.	Location			Date completed	Type of well	Depth of well (feet)	Casing	
									Pit	
			Sec.	T.S.	R.W.				Length (feet)	Diameter (inches)
Cu-211	Shell Pipe Line Corp.		35	8	10	1942	Dr	335		
213	Newport Industries	8	18	7	10	1932	Dr	658		12
214	do	9	18	7	10	1934	Dr	346		12
215	do	10	18	7	10	1937	Dr	365		12
216	do	11	18	7	10	1937	Dr	608		16
217	do	12	18	7	10	1939	Dr	610		18
218	do	1	18	7	10		Dr	679		
219	Humble Oil Co.		32	7	10		Dr	300		
225	Shell Pipe Line Co.		20	10	12	1942	Dr	338		
226	Ed. Broussard		6	11	12	1928	Dr	500		
227	E. Garrie		29	9	12	1941	Dr	426		
228	R. Royer		14	9	12	1934	Dr	425		
230	E. Wilson		22	9	12		Dr	700±		18
233	E. Wright		1	10	12		Dr	535	100	18
238	Charles Millet Est.		29	9	11		Dr	500		
241	T. Stegall		34	9	11	1944	Dr	420	100	18
242	D. Hope		1	10	11		Dr	355		
243	E. Hoffpauir		26	9	10		Dr	500±		24
245	W. Keever		34	8	10		Dr	300±		24
252	W. Pickett		5	11	11		Dr	397		
255	W. Burton		20	11	11		Dr	515		
256	M. Grey		1	11	12		Dr	516		
261	W. S. Green		5	11	10		Dr	600		
263	M. Drost		3	11	10		Dr	560	100	18
264	do		3	11	10		Dr	525		
270	A. Ihle		23	10	9	1940	Dr	212		4
289	D. Carathers		24	10	9		Dr	455		
291	C. Heard		14	10	9	1939	Dr	480		
295	H. Guth		25	10	9	1917	Dr	308		
345	J. Abrahams		17	10	8	1930	Dr	460		
347	J. Waite		26	9	7	1909	Dr	280		24
349	J. Stevens		3	10	8	1937	Dr	575		4
357	S. Guidry		27	9	8	1940	Dr	468		
360	T. Gormley		27	9	8		Dr	700		
364	S. Vincent		10	11	10	1943	Dr	575		24
373	H. Hoffpauir		10	10	10	1936	Dr	385		
389	B. Carr		13	9	9	1940	Dr	171		
409	J. Sutherland		35	9	9	1943	Dr	198		
411	Bob Lee Lumber Co.		26	9	9	1942	Dr	426		
420	G. Anderson		35	9	9		Dr	200		
423	Kelly-Weber Co.		36	9	9	1940	Dr	210		
424	J. Micelle Packing Co.		12	10	9		Dr	500±		
425	Southern Pacific RR.		32	9	8		Dr	385		
429	U.S. Air Force		2	10	8	1941	Dr	682	200	10
430	do		2	10	8	1941	Dr	684		10
431	J. Harrop		2	10	8	1918	Dr	640±		24
438	E. Hebert		11	9	10		B	20		
440	U.S. Air Force		2	10	8		Dr	500±		
442	do		2	10	8	1941	Dr	682	201	10
443	do		2	10	8	1941	Dr	684	206	10
444	do		2	10	8	1942	Dr	553		12
445	Cities Service Ref. Corp.		18	10	9	1945	Dr	540		18
446	do		18	10	9	1945	Dr	738		18
447	Town of Maplewood		31	9	9	1943	Dr	493	195	10
448	do		32	9	9	1943	Dr	496	200	10
449	Olin Mathieson Chemical Corp.	7	34	9	9	1945	Dr	517	262	18

Calcasieu Parish, La.—Continued

Casing: Well: Length (feet)	Casing: Well: Diameter (inches)	Screened interval (feet)	Aquifer	Static water level below or above (+) land-surface datum: Feet	Static water level: Date	Yield (gpm)	Use of water	Remarks
	7		"500-ft"	5	November 1942		D	
		574–658	"700-ft"				A	
	8	283–346	"500-ft"				N	
	8	305–365	"500-ft"	40	October 1943		N	C.
	10		"700-ft"				I	L.
	10	530–610	"700-ft"			1,350	I	
			"700-ft"				N	
	4		"500-ft"	27 51	April 1944 September 1956		I	C.
	7	308–338	"500-ft"	6 24	November 1942 April 1956		I	C.
	2½		"500-ft"				A	C. Flowed until 1932.
			"500-ft"	8	October 1943		D	
405	4	405–425	"500-ft"	11 45	do October 1956		D	C.
	16		"700-ft"				Ir	
345	12	435–535	"500-ft"	11 41	November 1943 August 1955		Ir	L.
	6		"500-ft"	10	November 1943		I	
227	10	320–420	"500-ft"	34	March 1955	2,750	Ir	L.
	4		"500-ft"	52	September 1956		D	
	12		"500-ft"	16	November 1943		Ir	
			"500-ft"	8 21	August 1945 September 1956		O	
385	2	385–397	"500-ft"				D	C.
	4	475–515	"500-ft"				D	
	4		"500-ft"	12 21	January 1950 March 1954		D	
	4		"500-ft"				D	Flowed until 1942.
375	12	463–563	"500-ft"				Ir	L.
	4	515–525	"500-ft"				D	C.
	2		"200-ft"	42	October 1941		D	C.
	2	445–455	"500-ft"				D	
	2		"500-ft"				D	
	4		"200-ft"				D	
450	2	450–460	"500-ft"				D	
	12	210–280	"200-ft"	30 36	October 1946 March 1955		A	C.
	2		"500-ft"				D	
457	2		"500-ft"				D	
	4		"700-ft"				D	
	10		"500-ft"	40	April 1956		Ir	
	4	373–385	"500-ft"				D	
	2		"200-ft"				D	
	2	188–198	"200-ft"				P	
	3	416–426	"500-ft"	22	July 1942		I	
	2		"200-ft"				D	
	3		"200-ft"				I	
	6		"500-ft"				I	
	12		"500-ft"				A	
415	6	615–682	"700-ft"	11	October 1942	500	P	
	6	618–684	"700-ft"	14	May 1942		A	
	12	540–640	"700-ft"	8	1942	2,500	A	
	36		Recent				D	C.
	4		"500-ft"	15 47	February 1944 September 1956		A	
612	6	662–682	"700-ft"	9	December 1941	515	A	C. Specific capacity 8 gpm per ft.
423	6	664–684	"700-ft"	9	do		P	L.
	8	500–553	"500-ft"	14	November 1942		P	
	10		"500-ft"	40 103	October 1945 September 1956		O	L.
	10		"500-ft"	33 82	October 1945 September 1956		O	L.
235	6	433–493	"500-ft"	26	June 1943	680	P	C, L. Specific capacity 14 gpm per ft.
280	6	433–493	"500-ft"	31 48	do July 1948	600	P	C. Specific capacity 24 gpm per ft.
123	6	394–517	"500-ft"	56 60	August 1945 November 1947	1,840	I	L.

TABLE 6.—*Description of wells in*

Well	Owner	Owner No.	Location			Date completed	Type of well	Depth of well (feet)	Casing	
									Pit	
			Sec.	T.S.	R.W.				Length (feet)	Diameter (inches)
Cu-450	Olin Mathieson Chemical Corp.		35	9	9	1945	Dr	523		18
451	Mr. Todd		3	11	7	1944	Dr	380		
452	R. Royer		23	8	12	1946	Dr	433		
453	C. Patterson		34	10	10	1947	Dr	345	101	20
454	Cities Service Ref. Corp.	J-20	19	10	9	1945	Dr	540	426	18
456	Paul Bellon		22	8	8	1948	Dr	436	141	20
457	Greater Lake Charles Water Co.	L	31	9	8	1946	Dr	696	575	16
458	Olin Mathieson Chemical Corp.	11	34	9	9	1948	Dr	509	359	18
459	do	10	34	9	9	1948	Dr	511	250	18
461	Petroleum Chemicals, Inc.	4	18	10	9	1945	Dr	522	426	18
462	Cit-Con Oil Corp.	1	13	10	10	1948	Dr	724	620	18
463	do	2	13	10	10	1948	Dr	533	400	18
464	do	3	13	10	10	1948	Dr	532	406	18
465	Olin Mathieson Chemical Corp.	9	34	9	9	1947	Dr	520	252	18
466	Columbia-Southern Chemical Corp.		20	9	10	1946	Dr	469		
467	do		20	9	10	1946	Dr	472		
468	J. Stevens		3	10	8	1940	Dr	412		
469	do		3	10	8	1944	Dr	495		
470	H. Landry		23	11	10	1948	Dr	287		
476	Union Sulphur Co.		21	11	10	1942	Dr	650		
477	do		17	11	10	1943	Dr	656		
478	do		35	11	12	1943	Dr	603		
479	do		35	11	12	1942	Dr	780		
483	U.S. Corps of Engineers.		21	11	9	1948	Dr	661	102	6
485	Pioneer Building		6	10	8	1948	Dr	518	420	10
486	Town of Westlake		26	9	9	1949	Dr	521	430	10
488	Vinton Petroleum Co.		33	10	12		Dr	600		
490	Krause and Managan		26	9	9		Dr	508		
492	Lakeside Laundry		31	9	8	1930	Dr	505		8
493	E. Daughenbaugh		29	10	7	1949	Dr	345		
494	J. Gayle		22	10	8	1949	Dr	577	160	20
495	Central La. Electric Co., Inc.		18	7	10	1948	Dr	660	584	12
496	do		18	7	10	1949	Dr	746	587	12
497	F. Helms		17	11	7		Dr	412		
498	J. E. Daigle		28	11	8	1948	Dr	703		
501	Greater Lake Charles Water Co.	M	30	9	8	1949	Dr	690		16
502	City of Sulphur		34	9	10	1949	Dr	573	520	10
504	Magnolia Petroleum Co.		30	10	9	1949	Dr	500		
505	Kansas City Bridge Co.		36	9	9	1948	Dr	508		
506	A. Coleman		13	9	9	1948	B	35		
507	R. Sherwood		11	9	9	1941	Dr	154		
508	B. Lee		25	9	9	1945	Dr	371		
509	L. Johnson		3	10	10	1947	Dr	383		4
510	do		9	9	10	1947	Dr	450		10
511	J. Stegall		34	9	11	1949	Dr	280		
512	T. Stegall		34	9	11	1946	Dr	393		
513	Ed. Stine		19	11	10	1945	Dr	593		4
514	Westlake Baptist Church.		35	9	9	1945	Dr	477		
515	M. Ellender		8	11	10	1948	Dr	570	120	18
516	Stein and Kinney		32	9	11	1941	Dr	401		4
517	H. Steward		12	8	9	1943	Dr	439	105	18

Calcasieu Parish, La.—Continued

Casing: Well: Length (feet)	Casing: Well: Diameter (inches)	Screened interval (feet)	Aquifer	Static water level below or above (+) land-surface datum: Feet	Static water level: Date	Yield (gpm)	Use of water	Remarks
	10	393–523	"500-ft"	59	August 1945	1,820	I	Specific capacity 32 gpm per ft.
	10		"200-ft"	30 42	January 1948 April 1956	3,100	Ir	
	8	348–433	"500-ft"			2,000	I	L, C.
20 159	10 9	270–345	"500-ft"	28 41	January 1948 April 1956	3,000	Ir	L, C.
93	10	430–540	"500-ft"	40	August 1945	1,500	I	
	12	351–436	"500-ft"	30 54	January 1948 September 1956		Ir	L, C.
137	10	575–696	"700-ft"	30	August 1946	1,500	P	
96	10	428–509	"500-ft"	80	1948	1,340	I	Specific capacity 25 gpm per ft.
205	10	430–511	"500-ft"	39 82	1947 1950	1,280	I	Specific capacity 55 gpm per ft.
92	10	420–522	"500-ft"	40	1945	1,500	I	
71	10	640–720	"700-ft"			1,280	I	L, C.
51	10	409–533	"500-ft"	61	1948	1,620	I	
49	10	310–405	"500-ft"	52	1948		I	
200	10	437–520	"500-ft"	36	August 1947	1,800	I	
			"500-ft"				I	
			"500-ft"				I	
	5		"500-ft"	36	September 1948		A	
	2	485–495	"500-ft"				D	
	2		"200-ft"	17	October 1948		D	
	5		"500-ft"				I	
	5		"500-ft"				I	
			"500-ft"				I	
	5		"500-ft"				I	
536	4	638–660	"500-ft"	30	October 1948		P	C.
63	6	468–518	"500-ft"				I	
101	6	451–521	"500-ft"	50	June 1949	670	P	L, C.
	6		"700-ft"				I	
			"500-ft"				I	
	4		"500-ft"				A	C.
		265–345	"200-ft"	67	September 1956		Ir	C.
384	12	497–577	"500-ft"	63	April 1956	4,000	Ir	C.
393	6	595–655	"700-ft"			375	P	C.
404	6	686–746	"700-ft"	83	July 1949	460	P	
			"200-ft"	63	September 1956		Ir	C.
		623–703	"500-ft"	52	do		Ir	L, C.
	10		"700-ft"	55	July 1949	1,760	P	
68	6	533–573	"500-ft"	37	August 1949	800	P	
	4		"500-ft"	44	do		D	
	4	488–508	"500-ft"				I	
			"500-ft"	11	January 1950		D	
	2	142–154	"200-ft"	36	October 1941		D	
	2	361–371	"500-ft"				I	
	3	371–383	"500-ft"				D	
	8	370–450	"500-ft"	28 53	January 1950 September 1956	2,500	Ir	L, C.
270	2	270–280	"200-ft"				D	
383	2	383–393	"500-ft"				D	
	2	573–593	"500-ft"				D	L.
467	2	467–477	"500-ft"				D	
399	10	490–570	"500-ft"	22 50	January 1950 September 1956		Ir	L, C.
	2	380–401	"500-ft"				I	C.
265	10	357–439	"500-ft"	35 45	January 1950 April 1956	1,400	Ir	C.

TABLE 6.—*Description of wells in*

Well	Owner	Owner No.	Location			Date completed	Type of well	Depth of well (feet)	Casing	
									Pit	
			Sec.	T.S.	R.W.				Length (feet)	Diameter (inches)
Cu-518	Todd Bros		3	11	7	1947	Dr	255		3
519	F. Helms		17	11	7	1948	Dr	367		20
520	D. Lavoi		8	11	6	1948	Dr	414	129	18
521	Calcasieu Parish School Bd.		7	11	5	1945	Dr	375		
522	Charles Brown		7	11	5	1943	Dr	316		3
523	Gulf Oil Co		18	11	5	1942	Dr	371		
524	Ed Taussig		15	10	9	1946	Dr	213		
525	Calcasieu Parish Police Jury.		15	10	9	1941	Dr	198		
526	O'Meara Brothers		33	10	12	1945	Dr	652		
527	N. Stanfa		34	9	8	1947	Dr	468		4
528	E. Wilson		21	9	12	1944	Dr	511		20
529	M. Gray		5	11	12	1945	Dr	276		
530	do		4	11	12	1948	Dr	595	120	20
531	do		1	11	12	1948	Dr	514	120	20
532	do		22	11	11	1948	Dr	568		20
533	Union Sulphur Co		16	11	10	1945	Dr	655		
534	W. Corbello		6	10	12	1947	Dr	550	100	18
536	G. K. Rowlins		8	8	8	1949	Dr	477	140	14
537	Lake Charles Country Club.		22	10	9	1948	Dr	759	720	7
539	Mayo and McFadder		4	9	8	1944	Dr	200		
541	C. Reeves and Savol		15	9	8	1945	Dr	480		
542	York Supply Co		27	9	8	1946	Dr	484		4
543	J. Metzger		18	10	6	1946	Dr	212		
544	C. Cornett		28	10	6	1945	Dr	277		
545	J. Doucet		8	10	6	1947	Dr	244	97	4
546	Union Sulphur Co		24	11	12	1943	Dr	535		
547	do		35	11	12	1943	Dr	599		
548	Circle Drilling Co		2	8	11	1949	Dr	250		
549	E. Dauchenbaugh		31	11	7		Dr	750		
550	C. Miller		15	8	8	1949	Dr	447	135	14
551	Alford Warehouse, Inc.		29	9	7	1950	Dr	460		
552	Olin Mathieson Chemical Corp.	5	34	9	9	1950	Dr	517		18
553	Greater Lake Charles Water Co.	N	31	9	8	1950	Dr	674	563	20
554	A. Bentley		30	7	10	1948	Dr	242	105	2
555	Town of Vinton		15	10	12	1950	Dr	602	502	12
556	Columbia-Southern Chemical Corp.	4	4	10	9	1950	Dr	697		16
557	General Box Co	1	29	8	12	1947	Dr	480		
558	do	2	29	8	12	1946	Dr	290		
559	do	3	30	8	12	1946	Dr	290		
560	Cities Service Ref. Corp.	J-120	19	10	9	1951	Dr	574	421	20
561	Continental Oil Corp.	8	34	9	9	1951	Dr	287		
562	E. Ledoux		11	9	8	1950	Du	22		
564	Church of the Nazarene.		4	9	8		Du	25		
565	F. Walker		15	9	9	1948	Du	33		
566	R. Young, Jr.		17	9	9	1948	Du	17		
567	H. White		11	9	8	1933	Dr	700±		
568	Dripps and Rauser		6	9	12	1951	Dr	450		
569	A. Cornier		23	8	13	1951	Dr	453		20
570	J. Johnson		33	8	11	1951	Dr	400		26
572	Stein and Kinney		12	9	13	1950	Dr	515		
574	Gulf States Utilities Co.	1	3	10	9	1947	Dr	707		12
575	do	2	3	10	9	1947	Dr	715		12
576	Olin Mathieson Chemical Corp.	13	34	9	9	1951	Dr	508	416	18

Calcasieu Parish, La.—Continued

Casing: Well: Length (feet)	Casing: Well: Diameter (inches)	Screened interval (feet)	Aquifer	Static water level below or above (+) land-surface datum: Feet	Static water level: Date	Yield (gpm)	Use of water	Remarks
	4	240–255	"200-ft"				I	L.
	11	287–367	"200-ft"	36	January 1950		Ir	
200	14	334–414	"200-ft"	15 39	January 1950 September 1956	2,000	A	
364	4	365–375	"200-ft"				D	
	2	306–316	"200-ft"				D	
361	2	361–371	"200-ft"				D	
		194–213	"200-ft"				D	
188	4	188–198	"200-ft"	15	February 1950		D	
620	7	620–652	"500-ft"	9	January 1950		I	
		458–468	"500-ft"				D	
	12		"500-ft"	20	January 1950		A	
259	4	261–276	"500-ft"	35	September 1955		D	
403	10	515–595	"500-ft"	30	September 1956		Ir	L
313	11	422–514	"500-ft"	12 34	January 1950 September 1956		Ir	C.
	12	220–280 552–592	"500-ft"	16 28	January 1950 March 1955		Ir	
633	5	633–655	"500-ft"				I	
358	10	490–550	"500-ft"	27	March 1956	2,800	Ir	L, C.
122	8	417–477	"500-ft"	53	September 1956		Ir	L, C.
84	4	727–759	"700-ft"				I	L, C.
190	2	190–200	"200-ft"				D	
460	4	460–480	"500-ft"				D	L.
	2	474–484	"500-ft"				D	
			"200-ft"				D	
265	2	265–275	"200-ft"				D	L.
145	3	234–244	"200-ft"				D	
514	4	513–534	"500-ft"				I	
578	4	577–598	"500-ft"				I	
	4		"200-ft"	28 34	March 1950 April 1956		I	
			"500-ft"	21 55	April 1946 September 1956		Ir	C.
22	10	363–447	"500-ft"	33	May 1950	2,500	Ir	C.
	2	450–460	"500-ft"	20	March 1950		I	
	10	429–517	"500-ft"	96	July 1950	1,500	I	
93	12	584–670	"700-ft"	60	September 1950	1,500	I	
126	1½	231–241	"200-ft"				D	
73	8	517–597	"500-ft"				P	L.
		597–697	"700-ft"			1,500	I	
	4		"500-ft"	20	July 1947		I	
	2		"500-ft"	30	July 1946		I	
	2		"500-ft"	30	do		P	
81	12	433–563	"500-ft"				I	Specific capacity 30 gpm per ft.
			"200-ft"				I	
	4		Recent	14	June 1951		D	C. Water salty.
			Pleistocene	10	do		D	C.
	10		do	10	do		D	
	30		do	12	do		D	
	10		"700-ft"	18	do		D	
	10		"500-ft"	31	October 1951	3,000	Ir	
	10		"500-ft"	22	do		Ir	L.
	12		"500-ft"	38 46	do September 1956		Ir	L, C.
	12	435–515	"500-ft"	30 46	October 1951 September 1956		Ir	L, C.
	8	626–707	"700-ft"	40	November 1946	800	I	Specific capacity 12 gpm per ft.
	8		"700-ft"	38	January 1947	800	I	Specific capacity 12 gpm per ft.
89	10	428–508	"500-ft"	88	October 1951	1,500	I	Specific capacity 54 gpm per ft.

TABLE 6.—*Description of wells in*

Well	Owner	Owner No.	Location			Date completed	Type of well	Depth of well (feet)	Casing	
									Pit	
			Sec.	T.S.	R.W.				Length (feet)	Diameter (inches)
Cu-577	Dripps and Rauser		8	9	12	1942	Dr	600		
578	F. Vail		17	11	8	1947	Dr	697		
579	Newport Industries	13	18	7	10	1947	Dr	652		18
580	Columbia-Southern Chemical Corp.	11	30	9	10	1946	Dr	469		12
581	do	12	30	9	10	1946	Dr	469		12
582	do	13	30	9	10	1951	Dr	609		18
583	do	3R	3	10	9	1951	Dr	670		18
584	U.S. Air Force	1	2	10	8	1952	Dr	577		
585	Jefferson Lake Sulphur Co.	1	19	9	12	1950	Dr	483	292	13
586	do	2	19	9	12	1950	Dr	495	401	16
587	Greater Lake Charles Water Co.	0	31	9	8	1952	Dr	674		
588	Davison Chemical Co.		25	10	10	1952	Dr	589	33	26
589	do		25	10	10	1952	Dr	585	33	
590	Petroleum Chemicals, Inc.	5	18	10	9	1953	Dr	551	30	26
591	do	6	18	10	9	1953	Dr	545	418	20
592	J. Reeves		4	9	8	1943	B	18		
594	C. Shavers		33	8	8	1953	B	16		
595	C. Long		34	8	8	1943	B	14		
596	L. Koonce		25	8	8		B	22		
597	F. Goos		2	9	8	1900	B	27		
598	L. Bryant		23	8	8		B	20		
600	A. Nolan		10	8	8	1947	B	15		
601	R. Lee		2	8	8		B	42		
603			22	8	7		B	28		
604	Ryan		15	8	7		B	21		
606	D. Miller		27	8	7	1950	Du	28		
610	W. Freeman		36	9	9	1942	Dr	285		
612	Jefferson Lake Sulphur Co.	3	19	9	12	1952	Dr	76		13
613	do	4	19	9	12	1952	Dr	85		13
614	M. Drost		3	11	10	1954	Dr	548		20
616	G. Wooster		27	10	10		Dr	350		
617	Petroleum Chemicals, Inc.	7	18	10	9	1954	Dr	530	401	20
619	Cities Service Ref. Corp.	J-142	19	10	9	1953	Dr	613		22
620	do	J-143	19	10	9	1953	Dr	561	426	22
621	Stein and Kinney		31	11	11	1944	Dr	585		22
622	Continental Oil Co.	9	36	9	9	1951	Dr	219		12
624	Davison Chemical Co.		25	10	10	1948	Dr	500±		
625	Stein and Kinney		11	8	13	1952	Dr	460		
627	Gulf States Utilities Co.	1	3	10	9	1953	Dr	558		12
629	Ohio Petroleum Co.		20	11	13		Dr	778		
630	M. Rosfield		34	10	9	1945	Dr	625		
631	Magnolia Petroleum Co.		1	9	7		Dr	200		
632	Mr. Coffey		22	8	9	1954	Dr	202		20
633	G. Natly		18	11	7	1954	Dr	300±		
635	E. Fontenot		6	10	11	1955	Dr	460		22
637	J. Lamkin and K. Breaux.		27	11	8	1955	Dr	585		16
639	Mrs. Managan		21	9	9	1950	Dr	487		12
640	J. Waite		26	9	7	1954	Dr	200		
641	Prairie Canal Co.		12	11	8	1951	Dr	365		18
642	F. Heyd		10	9	7	1949	Dr	287		14
643	Sweet Lake Land Co.		7	8	8	1954	Dr	424		12
644	Mr. Reeves		4	8	8	1946	Dr	426		18

Calcasieu Parish, La.—Continued

Casing: Well: Length (feet)	Casing: Well: Diameter (inches)	Screened interval (feet)	Aquifer	Static water level below or above (+) land-surface datum: Feet	Static water level: Date	Yield (gpm)	Use of water	Remarks
	12		"500-ft"	26 29	December 1951 March 1955		Ir	C.
	14		"500-ft"	20	August 1947	3,800	Ir	
	10	570–652	"700-ft"			1,000	I	
	8	389–469	"500-ft"	31	October 1946	600	I	Specific capacity 18 gpm per ft.
	8	389–469	"500-ft"	31	November 1946	600	I	
	8	509–609	"700-ft"	44	December 1951	1,000	I	Specific capacity 19 gpm per ft.
	10	550–650	"700-ft"	85	do	1,500	I	Specific capacity 24 gpm per ft.
	8	500–577	"500-ft"	42	January 1954	630	P	C.
	8	411–480	"500-ft"	43	September 1956	1,000	A	C. Original yield 1,000 gpm.
343	8	401–454 466–484	"500-ft"			1,100	I	
							P	
493 104	20 10	506–586	"500-ft"	46	1952	2,000	I	C. Specific capacity 41 gpm per ft.
490 108	20 10	506–586	"500-ft"	46	1952	2,000	I	C.
417 91	20 12	433–551	"500-ft"	84	January 1953	2,000	I	C. Specific capacity 63 gpm per ft.
85	12	427–547	"500-ft"	71	February 1953	2,030	I	Specific capacity 54 gpm per ft.
	5		Recent	6	April 1953		D	
	8		do	4	do		D	
	6		do	4	do		D	
	6		Pleistocene	12	do		D	
	8		Recent	22	do		D	
	8		Pleistocene	6	do		D	
	6		do	6	do		D	
	6		do	14	do		D	
	24		do	20	1953		D	
	24		do	18	1953		D	
	36		do	20	August 1953		D	
	4		"200-ft"	61	September 1956		O	
50	8	50–72	Pleistocene	14	August 1952	250	I	C.
	8	63–85	Recent	22	September 1952	250	I	C.
	10	468–548	"500-ft"	59	September 1956	2,500	Ir	C.
	3		"500-ft"	65	July 1954		I	
83	12	410–530	"500-ft"	79	May 1954	1,500	I	Specific capacity 55 gpm per ft.
	12	490–610	"500-ft"	93	October 1953	2,050	I	Specific capacity 50 gpm per ft.
84	12	438–558	"500-ft"	96	August 1953	2,050	I	Specific capacity 33 gpm per ft.
	10	505–585	"500-ft"	30	September 1956		Ir	L.
	7	185–217	"200-ft"	67	September 1951	284	I	Specific capacity 24 gpm per ft.
			"500-ft"	56	March 1955		D	
	12	310–460	"500-ft"	40	September 1956	2,400	Ir	L, C.
	8	488–558	"500-ft"				I	
	5		"500-ft"	21	September 1956		I	
	10		"500-ft"	56	April 1956	2,500	Ir	C.
	4		"200-ft"	38	do		I	
	12	142–204	"200-ft"	37	September 1956	4,500	Ir	L, C.
	10		"200-ft"	36	February 1955		Ir	
	10		"500-ft"	46	September 1956	3,800	Ir	C.
	8		"500-ft"	41	April 1956		Ir	L, C.
	8	410–470	"500-ft"	76	September 1956		Ir	C.
	12	140–200	"200-ft"	53	do		Ir	C.
	10	265–365	"200-ft"	37	February 1955		Ir	L.
	8		"200-ft"	40 22	do 1949	2,000	Ir	C.
	8		"200-ft"	52	February 1955	1,800	Ir	
	10		"200-ft"	53	do		Ir	

TABLE 6.—*Description of wells in*

Well	Owner	Owner No.	Location			Date completed	Type of well	Depth of well (feet)	Casing	
									Pit	
			Sec.	T.S.	R.W.				Length (feet)	Diameter (inches)
Cu-645	Sweet Lake Land Co.		29	8	8	1951	Dr	445		
646	J. Metzger		18	10	6	1955	Dr	330		20
647	Sweet Lake Land Co.		10	11	7	1918	Dr	400±		
649	Olin Mathieson Chemical Corp.	14	34	9	9	1952	Dr	522		20
651	D. W. Abbott		29	9	6	1953	Dr	400	121	16
652	do		29	9	6	1953	Dr	400	121	16
653	Krause and Managan.		11	9	10	1955	Dr	568		
654	Continental Oil Co.	10	27	9	9	1955	Dr	536		16
655	City of Sulphur		34	9	10	1955	Dr	585		
656	Lowe Estate		19	9	6	1910	Du	15		
660	Petroleum Chemicals, Inc.		18	10	9	1956	Dr	548	415	20
661	Greater Lake Charles Water Co.	S	6	10	8	1956	Dr	732	634	20
663	City of Westlake		26	9	9	1956	Dr	535	457	12
664	Cit-Con Oil Corp	4	13	10	10	1956	Dr	501	389	18
665	Gulf States Utilities Corp.		9	9	9	1956	Dr	473	379	16
666	do		9	9	9	1956	Dr	990	80	10
667	do		9	9	9	1956	Dr	457		
668	Lake Charles Air Force Base.		14	10	8	1956	Dr	200	162	8
669	do		14	10	8	1956	Dr	196	154	8
670	do		12	10	8	1956	Dr	113	81	3
671	do		11	10	8	1954	Dr	418		
672	do		10	10	8	1954	Dr	86	73	3
675	do	2	2	10	8	1946	Dr	511	436	
676	Cities Service Ref. Corp.	12	19	10	9	1957	Dr	553	420	22

Calcasieu Parish, La.—Continued

Casing: Well: Length (feet)	Casing: Well: Diameter (inches)	Screened interval (feet)	Aquifer	Static water level: Feet	Static water level: Date	Yield (gpm)	Use of water	Remarks
--------	10	----------	"200-ft"	41	January 1955	--------	Ir	
--------	10	----------	"200-ft"	47	February 1955	--------	Ir	L.
--------	--------	----------	"200-ft"	28	-----do	--------	Ir	
--------	10	402–522	"500-ft"	--------	--------	--------	I	
210	9	317–397	"200-ft"	--------	--------	--------	P	L, C.
210	9	317–397	"200-ft"	--------	--------	--------	P	
							T	L.
--------	10	435–535	"500-ft"	84	September 1955	2,000	I	L. Specific capacity 50 gpm per ft.
--------	10	485–585	"500-ft"	58	November 1955	--------	P	L.
--------	36	----------	Pleistocene	11	-----do	--------	D	C.
93	12	425–545	"500-ft"	105	August 1956	2,000	I	Specific capacity 44 gpm per ft.
100	12	649–729	"700-ft"	58	May 1956	1,800	P	C. Specific capacity 72 gpm per ft.
--------	8	485–535	"500-ft"	88	September 1956	500	P	Specific capacity 17 gpm per ft.
96	10	400–500	"500-ft"	93	-----do	2,000	I	Specific capacity 25 gpm per ft.
106	8	390–470	"500-ft"	62	June 1956	1,700	I	Specific capacity 36 gpm per ft.
{163 755}	{8 6}	930–990	Evangeline	49	July 1956	220	A	L. Salt-water supply; originally drilled to 2,204 feet. Specific capacity 2 gpm per ft.
445	4	435–445	"500-ft"	--------	--------	--------	O	
35	6	175–198	"200-ft"	--------	--------	--------	P	Ordnance area well 1.
56	6	175–195	"200-ft"	--------	--------	--------	P	C. Ordnance area well 2.
21	2	101–111	Pleistocene	--------	--------	--------	S	C. Transmitter station.
407	4	407–417	"500-ft"	53	December 1956	--------	P	Radar control building.
5	2½	76–86	Pleistocene	--------	--------	50	S	Receiver station.
--------	--------	480–511	"500-ft"	--------	--------	450	P	C.
30	12	430–550	"500-ft"	120	August 1957	2,000	I	Specific capacity 70 gpm per ft.

TABLE 7.—*Selected chemical analyses of water from wells in Calcasieu Parish*

Analyst: U.S. Geological Survey, Quality of Water Branch, unless otherwise indicated: A, Jefferson Lake Sulphur Co., Vinton, La.; B, Olin Mathieson Chemical Corp.; C, Columbia-Southern Chemical Corp.; D, Davison Chemical Co.; E, Petroleum Chemicals, Inc.; F, Cit-Con Oil Corp.; G, Greater Lake Charles Water Co. (these six in Lake Charles, La.); U, U.S. Geological Survey, Ground Water Branch, Baton Rouge, La.

[Well locations shown on plates 1 and 2]

Well	Date of collection	Chemical constituents (parts per million)																	Specific conductance (micromhos at 25° C)	Color	pH	Temperature (°F)	Analyst
		Silica	Total iron	Iron in solution	Calcium	Magnesium	Sodium	Potassium	Bicarbonate	Carbonate	Sulfate	Chloride	Fluoride	Nitrate	Boron	Dissolved solids	Hardness as $CaCO_3$	Carbon dioxide, calc.					
DEPOSITS OF RECENT AGE																							
Cu-438	12- 9-43		0.8						14		44	133	1.0				51				6.8		
562	10- 8-51	64	.7	0.02					248			1,320					1,390		5,650		8.2	72	
DEPOSITS OF PLEISTOCENE AGE																							
Shallow sands																							
Cu-612	5-16-55	35										257				549	138						A
613	5-16-55	35										445				900	240						A
656	11- 8-55											64										67	U
"200-foot" sands																							
Cu- 90	12- 8-43		0.10						224		1	28	0.4				111				7.6		
130	12- 8-43		.04						216		2	151	.6				120				7.5		
144	7-15-48		1.8						224	0		151	.0				142		862		7.7		
	7-28-55											150										71	U
146	7-15-48		3.0						262	18		139	.0				168		1,020		8.2		
	5-16-55											140										71	U
157	5- ?-43	37	.04		30	11	111		362	0	0.3	44	.5	0.0		403	120				8.0		
161	6-13-46		1.1						290			104		.0			110				7.5		
	5-16-55	34	.23	0.01	25	6.9	124	1.9	254	0	.2	114	.2	.5	0.13	433	91	16	756	0	7.4	73	

165	6- 7-49											55							733				
171	7-15-48		2.2						192	20		165	.0				144		898		8.6		
209	8-11-49											45							345				
270	7-26-55											22											U
347	7-19-48		8.5						230	18		294	.1				144		1,340		8.6		
493	6- 9-49											19							279				
	6-22-55											76										72	U
497	6-23-55											56										73	U
561	2-24-56	32	.33	.19	35	8.4	47	1.8	221	0	.5	32	.1	.2	.08	270	122	11	429	5	7.5	73	
632	6-21-55											24										71	U
640	6-24-55	48	0.21	0.01	54	21	189	3.6	255	0	3.6	300	.0	.2	1.1	748	221		1,440	0	7.8	72	
642	2-23-55											232										72	U
651	6-23-55											168											U
668	1-10-57	32	.30	.04	23	7.8	75		245	0	0	36	.1	.2		295	89	12	474	0	7.5	72	
669	1-10-57	20	.47	.02	20	7.8	98		290	0	0	40	.1	.3		330	82	15	549	0	7.5	72	

"500-foot" sands

Cu- 1	10-25-49	46	0.64		27	8.5	99	6.4	193	0	2.8	113	0.4	0	0.08	398	102		659	10	7.4	73	
71	8-28-40								170		4	39	.3				108						
78	5-24-55	53	1.8								2.6	47					109				8.4	74	B
83	7-18-50	65	1.6		36	8.7	35	.4	168	0	4.2	44	0	0	.06	276	126	1.3	417		8.3	74	
85	8-25-48		2.7						192			33	.1				135		400		7.6		
91	2-24-56	56	2.0	.08	32	7.8	38	2.7	161	0	3.3	44	.2	.0	.02	268	112	16	390	5	7.2	74	
97	8-18-49											20							360				
	7-18-50	64	1.1		34	7.8	30	2	182	0	4.9	21	.2	.0	.04	253	117	1.1	355		8.4	75	
118	10-25-49	58	2.4	1.3	20	7.9	28		139	0	2.0	20	.0	.0		204	82		276		7.6		
119	8-11-49											22							293				
120	8-20-39								248		1	26	.0				90						
127	12- 8-43		.16						199		2.0	75	.6				114				7.6		
163	6-23-55											40										76	U
205	5- 7-46		1.9									33					84					73	
208	5-17-55	62	8.1	.14	16	5.3	30	2.6	92	0	4.9	36	.3	.2	.07	203	62	23	282	20	6.8	72	
215	7-27-49	56	2.4		13	4.2	22		85	0	5.9	21	.0	0	.47	175	56		221		6.7	71	
219	5-19-55											34										70	U
225	6- 9-49											14							439				
226	6- 9-49											90							703				
228	5-19-55											20										71	U
252	12- 8-43		.06						232		2	22	1.0				84				7.5		
264	12- 8-43		3.8						244		4	19	1.2				123				7.7		
447	4- 6-51	48	.74	.00	28	7.0	37	6	176	0	3.0	26	.2	.2	.15	243	99	8.8	356		7.5	74	
452	5-25-55	53	3.8	.27	21	7	40	2.4	149	0	3.7	33	.4	.2	.08	234	81	30	361	20	6.9	71	
453	5-26-55	47	.28	.00	42	7.3	35	1.9	236	0	.8	16	.1	.0	.04	267	135	5	410	0	7.9	72	
456	7-15-48		11						120			32	.0				80		301		8.2		
483	7-26-55											28										74	U
486	10-25-49	54			30	9	37		161	0	3.0	40	0.0	0.0		252	112		371		8.0		
492	6- 9-49											43							400				
494	5-25-55											88										75	U

TABLE 7.—*Selected chemical anylses of water from wells in Calcasieu Parish*—Continued

[Well locations shown on plates 1 and 2]

Well	Date of collection	Chemical constituents (parts per million)																	Specific conductance (micromhos at 25° C)	Color	pH	Temperature (°F)	Analyst
		Silica	Total iron	Iron in solution	Calcium	Magnesium	Sodium	Potassium	Bicarbonate	Carbonate	Sulfate	Chloride	Fluoride	Nitrate	Boron	Dissolved solids	Hardness as $CaCO_3$	Carbon dioxide, calc.					
"500-foot" sands—continued																							
Cu-498	5-25-55											62										77	U
510	5-27-55											24										72	U
515	6-24-55											20										74	U
516	7-27-55											32										73	U
517	7-26-55											48										73	U
531	6-21-55											116										79	U
534	5-17-50	48	1.1		21	6.4	50	5.2	179	0	3.1	31	.4	.02	0.18	257	79		387		7.3	75	
536	6-22-55											40										73	U
549	5-16-55											34										72	U
550	5-17-50	58	4.9		17	6.5	32	4.4	106	0	6.6	33	.3	.0	.08	214	69		291		6.8	73	
570	6-21-55											116											U
572	6-21-55											36										73	U
577	6-22-55											20										74	U
584	1-11-55	53	.73	0.00	41	9.7	48		187	0	2.7	64	.1	.2		309	142		483	0	8.2	75	
585	6-18-51		2.0						127	18		270				479	78	0.0		47	7.8		F
	2-26-52		.6						293	0		907				1,030	70	11		23	8.0		F
588	2-24-56	54	1.9	.10	35	6.7	38	2.6	204	0	.5	24	.2	.2	.04	267	116	10	380	5	7.5	74	

589	5-16-55	40										35					126						D
590	5- 8-56	58	1.5								2	20				265	142				7.4		E
614	6-21-55											28										75	U
625	5-19-55	58	3.0	1.8	17	5.2	24	2.3	119	0	3.2	14	.2	.2	.0	186	64	6	238	80	7.5	73	
630	5-25-55	48	.36	.03	34	7.0	53	2.3	236	0	.1	28	.1	.0	.06	294	114	12	450	0	7.5	76	
635	6-21-55											20											U
637	5-25-55											100										76	U
639	5-17-55	58	2.6	.36	25	6.9	32	2.7	143	0	3.4	32	.3	.2	.04	231	91	2	341	15	8.1	73	
675	1-10-57	52	.67	.05	43	8.2	52		189	0	1.8	70	.1	.2		324	142	12	510	0	7.4	73	
59 [1]	6-21-55											516										76	U

"700-foot" sands

Cu- 3	7-15-40								175		3	91	0.0				99						
	8-24-48		5.6						166			95	.0				110		571		7.9		
	4-21-52	56	3.9	0.39	31	9.7	74	2	166	0	2.7	101	.3	0.2	0.08	366	118		607	0	7.3	75	
	6-28-55											146										75	U
	9-25-56											156											U
7	8-21-40								246		1	29	1.0				33						
31	8-20-51								162			66					110		477		7.8		
	12-18-56											104											G
84	8-11-49											34							400				
92	5- 2-44		2.3						196		2	161	.2				114				8.0		
	7-18-50	58	1.9		32	9	95	1.6	182	0	2	120	.0	.0	.06	407	117	1.5	677		8.3	76	
	2-24-56	51	13	.05	37	10	143	3.5	203	0	1	195	.2	.2	.07	557	133		934	5	7.3	76	
98	8- 7-44	40	.4						173		4	114				390	107	8			7.3		
	7-18-50	58	1.1		51	16	190	2	202	0	1.9	306	.1	0	.21	740	193	1.6	1,300		8.3	78	
99	8-25-48		3.1						176			81	.0				92		543		7.9		
	5-17-55	53							184			116					81				7.2		C
100	8-25-48		1.7						178			40	.0				116		413		7.9		
	5-17-55	55							178			105					82				7.2		C
108	8-18-49											160							897				
151	6-22-55											316										78	U
173	7-15-48		3.0						180	22		294	.0				168		1,300		8.6		
	8- 1-56											296										76	U
442	10- 2-42		1.3		40				192		5	57				295	144				7.1		
462	8-17-55	45	.9									216				585	214			5	7.1		F
495	9-12-50	50	.86	.64	9.7	2.0	36	9.2	115	0	2.5	16	.2	.0	.18	184	32		244		7.1	74	
537	7-26-56											182										78	U
661	9-24-56											88											U
	12-18-56											100											G

[1] Well in sec. 6, T. 12 S., R. 11 W., Cameron Parish.

TABLE 8.—*Drillers' logs of representative wells in Calcasieu Parish*

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Cu-6. Central Louisiana Electric Co., DeQuincy [Sec. 18, T. 7 S., R. 10 W.]					
Soil	6	6	Gumbo	28	401
Clay	37	43	Shale, sandy, gumbo	168	569
Clay, sandy	22	65	Sand, fine, dirty	15	584
Gumbo	6	71	Sand	38	622
Shale, sandy	32	103	Gumbo	6	628
Sand	20	123	Sand	26	654
Gumbo	81	204	Gumbo	5	659
Sand, coarse, and gravel	169	373			
Cu-22. Magnolia Petroleum Co., Lake Charles [Sec. 8, T. 10 S., R. 9 W.]					
Clay	40	40	Sand and gravel	70	442
Sand and gravel	18	58	Shale	50	492
Sand	54	112	Sand and gravel	85	577
Gravel	190	302	Shale, sticky	75	652
Shale, sticky	70	372			
Cu-33. Greater Lake Charles Water Works Co., Lake Charles [Sec. 31, T. 9 S., R. 8 W.]					
Clay	18	18	Gumbo	84	315
Sand, white	51	69	Sand, fine, black	188	503
Clay	48	117	Sand, coarse	19	522
Sand, soft	17	134	Gumbo	12	534
Clay, sandy	97	231	Sand and gravel	152	686
Cu-46. Missouri Pacific RR., Lake Charles [Sec. 9, T. 10 S., R. 8 W.]					
Soil	4	4	Gravel	45	358
Clay	10	14	Gumbo	40	398
Sand, red	34	48	Sand, fine	46	444
Clay	153	201	Sand, coarse	75	519
Shale	45	246	Sand and gravel	45	564
Shale, sandy	67	313			
Cu-74. Firestone Tire and Rubber Co., Lake Charles [Sec. 18, T. 10 S., R. 9. W.]					
Soil	12	12	Gumbo	86	386
Sand, red	28	40	Sand	169	555
Clay	12	52	Shale	60	615
Shale	110	162	Gumbo	10	625
Shale, sandy	22	184	Sand	105	730
Sand	96	280	Gumbo	10	740
Sand and shale	20	300			

TABLE 8.—*Drillers' logs of representative wells in Calcasieu Parish*—Continued

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Cu-75. Firestone Tire and Rubber Co., Lake Charles [Sec. 18, T. 10 S., R. 9 W.]					
Soil	2	2	Sand, fine	25	664
Clay	8	10	Shale	2	666
Sand, red	5	15	Sand	38	704
Clay	177	192	Shale	7	711
Sand	82	274	Sand	40	751
Shale	113	387	Shale	11	762
Sand	179	566	Sand, fine	21	783
Shale	73	639	Sand	114	897
Cu-96. Petroleum Chemicals, Inc., Lake Charles [Sec. 18, T. 10 S., R. 9 W.]					
Soil	2	2	Sand	167	561
Sand, red	28	30	Shale, gummy	37	598
Clay	20	50	Sand	15	613
Shale	152	202	Shale	7	620
Sand	28	230	Sand	116	736
Shale	164	394	Shale	20	756
Cu-98. Petroleum Chemicals, Inc., Lake Charles [Sec. 18, T. 10 S., R. 9 W.]					
Shale	200	200	Shale	49	391
Sand	35	235	Sand	166	557
Shale	55	290	Shale	47	604
Sand	52	342	Sand	163	767
Cu-99. Columbia-Southern Chemical Corp., Lake Charles [Sec. 3, T. 10 S., R. 9 W.]					
Clay, yellow	70	70	Sand, streaky, and gumbo	26	436
Sand, fine	6	76	Sand	98	534
Gumbo	78	154	Gumbo	20	554
Sand, coarse	7	161	Shale, sandy	10	564
Gumbo	9	170	Sand	105	669
Sand, coarse	100	270	Shale and sand	3	672
Gumbo	3	273	Sand	93	765
Sand	6	279	Shale, streaky	6	771
Gumbo	19	298	Sand	32	803
Shale, sandy	82	380	Gumbo	64	867
Sand	30	410			
Cu-108. Union Oil of California, Lake Charles [Sec. 33, T. 10 S., R. 12 W.]					
Soil	9	9	Sand	30	310
Gumbo, shells	15	24	Shale	86	396
Gumbo	62	86	Sand	19	415
Sand	34	120	Gumbo	195	610
Gumbo	160	280	Sand and gravel	58	668

TABLE 8.—*Drillers' logs of representative wells in Calcasieu Parish*—Continued

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Cu-112. I. V. Maurer, Westlake [Sec. 25, T. 9 S., R. 9 W.]					
Soil	2	2	Shale	12	157
Clay	128	130	Sand, medium to coarse	54	211
Sand, fine	15	145			
Cu-114. F. P. Friesen, Lake Charles [Sec. 29, T. 11 S., R. 8 W.]					
Soil	18	18	Sand, shale with shells	353	536
Sand	30	48	Sand, fine	37	573
Clay	124	172	Sand, coarse	129	702
Sand	11	183			
Cu-126. Swift Packing Co., Lake Charles [Sec. 1, T. 10 S., R. 8 W.]					
Clay	38	38	Gumbo	212	415
Sand, coarse, yellow	9	47	Sand	42	457
Clay	142	189	Sand and gravel	53	510
Shale, sandy	14	203			
Cu-135. Shell Oil Co., Lake Charles [Sec. 6, T. 11 S., R. 9 W.]					
Soil	12	12	Gumbo	100	451
Sand, fine	5	17	Sand, fine	30	481
Clay	303	320	Sand, medium	45	526
Shale	31	351			
Cu-136. Shell Oil Co., Lake Charles [Sec. 23, T. 9 S., R. 7 W.]					
Clay	62	62	Sand, coarse, and gravel	54	204
Sand, fine	8	70	Sand, coarse, and gravel	39	243
Clay	22	92			
Sand, fine, gray	58	150			
Cu-137. Shell Oil Co., Lake Charles [Sec. 30, T. 9 S., R. 6 W.]					
Clay	17	17	Clay	55	84
Sand	12	29	Sand	222	306
Cu-147. J. Metzger, Lake Charles [Sec. 18, T. 10 S., R. 6 W.]					
Clay	15	15	Sand, coarse, gray	40	187
Sand, red	12	27	Sand, coarse, and gravel	169	356
Clay, yellow	80	107	Gumbo, blue	3	359
Sand, fine, black	40	147			

TABLE 8.—*Drillers' logs of representative wells in Calcasieu Parish*—Continued

Cu-156. O. Primo, Rt. 2, Iowa
[Sec. 35, T. 10 S., R. 7 W.]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, top	10	10	Sand, fine	90	291
Sand	8	18	Gravel	165	456
Clay, yellow	183	201			

Cu-159. E. Fruge, Lake Charles
[Sec. 25, T. 11 S., R. 7 W.]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Clay	10	10	Gumbo	25	175
Shells	6	16	Sand, hard, gray	140	315
Gumbo	99	115	Sand, coarse, white	115	430
Sand, hard, and shale	35	150			

Cu-165. Walter Helm, Lake Charles
[Sec. 29, T. 11 S., R. 7 W.]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, surface	2	2	Clay, sandy	10	200
Clay	12	14	Sand	193	393
Sand, fine	8	22	Gumbo	7	400
Clay	128	150	Shale, hard, sand	6	406
Clay, streaky	40	190			

Cu-172. E. Cobena, Lake Charles
[Sec. 2, T. 11 S., R. 8 W.]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil	2	2	Clay and shale	305	390
Clay	6	8	Sand, fine	41	431
Sand, red	4	12	Shale, gummy	99	530
Clay	58	70	Sand, fine	14	544
Sand, fine, white	15	85	Sand	95	639

Cu-173. C. Linkswiler, Lake Charles
[Sec. 26, T. 10 S., R. 8 W.]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil, top	10	10	Clay, blue	55	438
Sand	24	34	Sand, fine, gray	91	529
Clay, blue	24	58	Clay, red	10	539
Sand, fine, gray	21	79	Sand, fine, gray	62	601
Clay, blue	64	143	Sand, gray	115	716
Sand, fine, gray	126	269	Sand and gravel	6	722
Clay, blue	20	289	Sand, coarse, gray	47	769
Sand, fine, gray	94	383			

Cu-186. V. M. Jones, Lake Charles
[Sec. 35, T. 9 S., R. 8 W.]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Gumbo	106	106	Sand	30	381
Sand, fine	22	128	Sand, white	133	514
Gumbo	223	351	Sand and gravel	138	652

TABLE 8.—*Drillers' logs of representative wells in Calcasieu Parish*—Continued

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Cu-208. W. Caldwell, Lake Charles [Sec. 6, T. 8 S., R. 8 W.]					
Soil	12	12	Sand, fine	15	306
Clay	21	33	Gumbo	32	338
Sand, fine	8	41	Sand	4	342
Clay	67	108	Shale, sticky	9	351
Sand, red	18	126	Sand and gravel	116	467
Clay	165	291			
Cu-216. Newport Industries, Lake Charles [Sec. 18, T. 7 S., R. 10 W.]					
Clay, red	99	99	Gumbo	27	387
Clay, yellow	46	145	Shale, sandy	44	431
Gumbo	22	167	Gumbo	61	492
Sand and gravel	73	240	Shale, sandy	62	554
Rock	2	242	Sand, fine	51	605
Sand	46	288	Shale	21	626
Rock	1	289	Sand	5	631
Sand and gravel	71	360	Gumbo	22	653
Cu-233. E. Wright, Lake Charles [Sec. 1, T. 10 S., R. 12 W.]					
Soil	2	2	Shale, sandy	150	400
Clay, yellow	8	10	Gumbo	10	410
Sand	5	15	Sand, fine, gray	10	420
Sand, yellow	135	150	Sand, coarse, and gravel	110	530
Shale, sandy	40	190	Gumbo	5	535
Sand, fine, gray	60	250			
Cu-241. T. S. Stegall, Lake Charles [Sec. 34, T. 9 S., R. 11 W.]					
Soil	4	4	Shale	40	200
Sand	11	15	Sand, fine	70	270
Sand, white	35	50	Sand, coarse	110	380
Shale	10	60	Sand, coarse, and gravel	40	420
Gumbo	60	120			
Sand, fine	40	160			
Cu-263. M. Drost, Lake Charles [Sec. 3, T. 11 S., R. 10 W.]					
Soil	10	10	Sand, fine	15	280
Sand, red	5	15	Shale	45	325
Clay, yellow	120	135	Sand, fine	20	345
Shale	40	175	Shale	110	455
Shale, sandy	25	200	Sand, coarse, and gravel	110	565
Sand, fine	20	220			
Shale	45	265			

TABLE 8.—*Drillers' logs of representative wells in Calcasieu Parish*—Continued

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Cu-443. U.S. Air Force, Lake Charles [Sec. 2, T. 10 S., R. 8 W.]					
Clay, sandy, red	48	48	Sand, coarse	40	364
Sand, coarse	12	60	Sand, medium	59	423
Gumbo	33	93	Sand, medium, coarse	67	490
Sand and gravel	7	100	Shale, sandy	23	513
Gumbo	40	140	Sand, hard	31	544
Clay	2	142	Shale and sand	23	567
Shale	103	245	Sand	118	685
Gumbo	59	304	Gumbo	16	701
Sand, fine	20	324			
Cu-445. Cities Service Refining Corp., Lake Charles [Sec. 18, T. 10 S., R. 9 W.]					
Soil	12	12	Gumbo and shale	130	389
Sand, red	28	40	Sand	153	542
Gumbo and shale	129	169	Shale	23	565
Sand	90	259			
Cu-446. Cities Service Refining Corp., Lake Charles [Sec. 18, T. 10 S., R. 9 W.]					
Soil	12	12	Sand	153	542
Sand, red	28	40	Gumbo and shale	58	600
Gumbo and shale	129	169	Sand	138	738
Sand	90	259	Gumbo	4	742
Gumbo and shale	130	389			
Cu-447. Town of Maplewood [Sec. 31, T. 9 S., R. 9 W.]					
Soil	2	2	Shale	98	218
Clay, sandy	10	12	Sand, shaly	18	236
Sand, red	18	30	Shale	144	380
Shale	20	50	Sand, medium	113	493
Clay	35	85	Shale	10	503
Sand, fine	35	120			
Cu-449. Olin Mathieson Corp., Lake Charles [Sec. 34, T. 9 S., R. 9 W.]					
Soil	3	3	Shale	107	367
Clay	48	51	Sand, fine	13	380
Shale	84	135	Sand, water	137	517
Sand	125	260	Gumbo	23	540
CU-452. R. Royer, Lake Charles [Sec 23, T. 8 S., R. 12 W.]					
Soil	2	2	Shale, gumbo	26	248
Clay, sandy	38	40	Shale, gumbo	39	287
Sand	47	87	Shale, sandy	18	305
Shale and gumbo	68	155	Sand, fine, gray	30	335
Shale, sandy	45	200	Sand, medium, gray	89	424
Gumbo	4	204	Sand, coarse, and gravel	11	435
Sand, medium, white	18	222			

TABLE 8.—*Drillers' logs of representative wells in Calcasieu Parish*—Continued

Cu-453. C. Patterson, Lake Charles
[Sec. 34, T. 10 S., R. 10 W.]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil	3	3	Shale, hard	90	170
Clay	12	15	Sand, fine	90	260
Sand	5	20	Sand	85	345
Shale	60	80			

Cu-456. Paul Bellon, Gillis
[Sec. 22, T. 8 S., R. 8 W.]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Clay	85	85	Shale, sandy	66	266
Sand	11	96	Sand, fine	43	309
Shale	59	155	Shale	4	313
Sand	8	163	Sand, medium	95	408
Shale	37	200	Sand, coarse	28	436

Cu-462. Cit-Con Corp., Lake Charles
[Sec. 13, T. 10 S., R. 10 W.]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Clay, white	15	15	Gumbo	59	399
Sand, fine	15	30	Sand, fine	159	558
Gumbo	134	164	Gumbo and shale	59	617
Sand, streaky	24	188	Sand, fine	68	685
Sand, fine	91	279	Sand and shale	12	697
Shale	51	330	Sand	36	733
Sand	10	340	Shale and gumbo	30	763

Cu-486. Town of Westlake
[Sec. 26, T. 9 S., R. 9 W.]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil	4	4	Shale, sandy	18	251
Clay, sandy	8	12	Shale	67	318
Sand	4	16	Shale, sandy	40	358
Clay	22	38	Sandy, fine	22	380
Shale	12	50	Shale	1	381
Sand	5	55	Sand	4	385
Shale	15	70	Sand, fine	64	449
Sand	3	73	Sand, medium	22	471
Shale, sticky	65	138	Sand, coarse	22	493
Sand	65	203	Sand, gravel	22	515
Shale	25	228	Sand, medium	6	521
Sand	5	233			

Cu-498. J. E. Daigle, Lake Charles
[Sec. 28, T. 11 S., R. 8 W.]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil	4	4	Shale, hard	126	450
Clay	14	18	Shale, sticky	10	460
Sand	4	22	Shale, sandy	29	489
Sand, fine	16	38	Shale	49	538
Clay, soft	49	87	Gumbo, hard	19	557
Sand, fine	11	98	Sand, fine	63	620
Gumbo	30	128	Sand and gravel	9	629
Shale, sticky	169	297	Sand, coarse	91	720
Sand, coarse	27	324	Sand, fine	60	780

TABLE 8.—*Drillers' logs of representative wells in Calcasieu Parish*—Continued

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Cu-510. L. Johnson, Sulphur [Sec. 9, T. 9 S., R. 10 W.]					
Soil	3	3	Shale	180	300
Shale	87	90	Sand, fine	50	350
Sand, fine	30	120	Clay, sandy	100	450
Cu-513. Ed. Stine, Lake Charles [Sec. 19, T. 11 S., R. 10 W.]					
Soil	3	3	Shale, hard	143	200
Clay	12	15	Shale, sandy	323	523
Sand	7	22	Sand, fine	37	560
Shale	28	50	Sand and gravel	40	600
Sand	7	57			
Cu-515. M. Ellender, Lake Charles [Sec. 8, T. 11 S., R. 10 W.]					
Clay	30	30	Shale, gummy	129	398
Shale, gummy	35	65	Shale, sandy	35	433
Shale and gumbo	45	110	Sand, fine	55	488
Sand and shale	119	229	Sand, medium	89	577
Shale	40	269			
Cu-518. Todd Bros., Lake Charles [Sec. 3, T. 11 S., R. 7 W.]					
Soil	3	3	Clay	65	108
Clay	4	7	Gumbo	62	170
Sand, red	13	20	Sand, fine	50	220
Gumbo	23	43	Clay, sand	35	255
Cu-530. M. Gray, Lake Charles [Sec. 4, T. 11 S., R. 12 W.]					
Soil	4	4	Sand	50	431
Clay	8	12	Shale	4	435
Sand	11	23	Sand	21	456
Clay	22	45	Shale	2	458
Sand, coarse	30	75	Sand, fine	136	594
Sand	165	240	Shale	68	662
Sand, fine	93	333	Sand	83	745
Shale	48	381	Boulder	5	750
Cu-534. W. Corbello, Lake Charles [Sec. 6, T. 10 S., R. 12 W.]					
Soil	3	3	Sand, fine	19	244
Gumbo	44	47	Shale, hard	22	266
Shale	20	67	Sand	34	300
Sand	13	80	Shale	28	328
Shale, sticky	40	120	Sand	35	363
Sand	20	140	Shale	44	407
Shale, hard	30	170	Sand, fine	36	443
Shale, soft	30	200	Sand	7	450
Sand	19	219	Sand, good	57	507
Shale, hard	6	225	Sand, coarse	43	550

TABLE 8.—*Drillers' logs of representative wells in Calcasieu Parish*—Continued

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Cu-536. G. K. Rowlins, Gillis [Sec. 8, T. 8 S., R. 8 W.]					
Clay, red	40	40	Shale	46	320
Sand, fine	40	80	Sand, fine	70	390
Shale	20	100	Shale	4	394
Gumbo	39	139	Sand	18	412
Shale	61	200	Shale	4	416
Gumbo and shale	50	250	Sand, coarse, and gravel	62	478
Shale, sandy	24	274			
Cu-537. Country Club, Lake Charles [Sec. 22, T. 10 S., R. 9 W.]					
Clay	20	20	Shale	180	680
Sand	10	30	Sand, fine	30	710
Shale	395	425	Shale	10	720
Sand, fine	75	500	Sand, coarse	40	760
Cu-541. C. Reeves and Savol, Lake Charles [Sec. 15, T. 9 S., R. 8 W.]					
Soil	3	3	Shale	290	350
Clay	52	55	Sand, fine	90	440
Sand	5	60	Clay, sand	45	485
Cu-544. C. Cornett, Bell City [Sec. 28, T. 10 S., R. 6 W.]					
Soil	3	3	Sand, fine	50	200
Clay	22	25	Sand, coarse	50	250
Sand	10	35	Gravel	27	277
Shale	115	150			
Cu-555. Town of Vinton [Sec. 15, T. 10 S., R. 12 W.]					
Clay	90	90	Sand	19	470
Sand	15	105	Clay	15	485
Clay	56	161	Sand	8	493
Unknown	9	170	Sand	4	497
Sand	125	295	Clay	7	504
Clay	95	390	Sand	94	598
Sand	30	420	Clay	2	600
Sand and clay	31	451	Sand	3	603
Cu-569. A. Cormier, Lake Charles [Sec. 23, T. 8 S., R. 13 W.]					
Clay, sandy	15	15	Sand	120	452
Sand, white	40	55	Sand, fine, sticky	38	490
Shale	277	332			
Cu-570. J. Johnson, Lake Charles [Sec. 33, T. 8 S., R. 11 W.]					
Clay	110	110	Shale, sandy	66	294
Sand, medium	46	156	Sand, medium	106	400
Shale, gummy	72	228			

TABLE 8.—*Drillers' logs of representative wells in Calcasieu Parish*—Continued

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Cu-572. Stein and Kinney, Starks [Sec. 12, T. 9 S., R. 13 W.]					
Soil	4	4	Sand	5	225
Clay	53	57	Shale	112	337
Sand, fine	8	65	Sand, fine	73	410
Sand, coarse	20	85	Sand, medium	16	426
Sand, gravel	8	93	Sand, coarse	24	450
Shale, sandy	77	170	Gravel	43	493
Sand, fine	33	203	Sand	19	512
Shale	17	220	Shale	3	515
Cu-621. Stein and Kinney, Starks [Sec. 31, T. 11 S., R. 11 W.]					
Soil	5	5	Shale	87	407
Gumbo	112	117	Gumbo	58	465
Gumbo	54	171	Sand	120	585
Sand, coarse	37	208	Sand, coarse	90	675
Gumbo	112	320	Gumbo	4	679
Cu-625. Stein and Kinney, Starks [Sec. 11, T. 8 S., R. 13 W.]					
Soil	4	4	Sand, fine	50	380
Clay	67	71	Sand, coarse, and gravel	80	460
Sand	39	110			
Shale	220	330			
Cu-632. Mr. Coffey, Lake Charles [Sec. 22, T. 8 S., R. 9 W.]					
Soil, and clay	75	75	Shale	10	214
Sand	129	204			
Cu-637. J. Lamkin and K. Breaux, Lake Charles [Sec. 27, T. 11 S., R. 8 W.]					
Soil	6	6	Shale, sandy	80	280
Sand, red	9	15	Sand	47	327
Clay, red	20	35	Shale	57	384
Clay, blue	25	60	Shale, sandy	77	461
Clay, sandy	60	120	Sand	124	585
Shale	80	200			
Cu-641. Prairie Canal Co., Lake Charles [Sec. 12, T. 11 S., R. 8 W.]					
Clay	8	8	Sand, fine	40	260
Sand	12	20	Sand, coarse	50	310
Shale	140	160	Sand, coarse, and gravel	61	371
Sand, fine	30	190			
Shale	30	220			

TABLE 8.—*Drillers' logs of representative wells in Calcasieu Parish*—Continued

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Cu-646. J. Metzger, Iowa [Sec. 18, T. 10 S., R. 6 W.]					
Soil	1	1	Shale	97	115
Clay	13	14	Sand, fine	120	235
Sand	4	18	Sand, coarse	95	330
Cu-651. D. W. Abbott, Welch [Sec. 29, T. 9 S., R. 6 W.]					
Soil	3	3	Shale	110	240
Clay	22	25	Sand, fine	60	300
Sand	5	30	Sand, coarse	20	320
Clay	100	130	Sand and gravel	80	400
Cu-653. Krause and Managan, Sulphur [Sec. 11, T. 9 S., R. 10 W.]					
Soil	2	2	Clay, brown, blue, gray, white with shell fragments	51	315
Clay, gray, buff	8	10	Sand, fine, black, red, green	42	357
Clay, gray	10	20	Sand, fine to coarse	33	390
Clay, brown	10	30	Clay	10	400
Clay, brown, grayish, silty	10	40	Clay, red, blue, brown, lignitic	20	420
Clay, brown, red, sandy	10	50	Wood, carbonized	3	423
Clay, brown, red, lignitic	10	60	Sand, coarse, and gravel	63	486
Clay, brown, red	20	80	Sand, coarse, and gravel with wood	22	508
Clay, brown, red, lignitic	20	100	Sand, coarse, and gravel	20	528
Clay, gray, red	110	210	Sand, fine to medium	20	548
Clay, red, gray, brown, lignitic	23	233	Sand, coarse, and gravel	5	553
Sand, fine to medium, white to grayish, salt and pepper	17	250	Clay, blue	15	568
Clay, brown, blue	14	264			
Cu-654. Continental Oil Co., Lake Charles [Sec. 27, T. 9 S., R. 9 W.]					
No log	50	50	Clay	135	420
Clay	105	155	Sand	145	565
Sand and gravel	130	285			
Cu-655. City of Sulphur, Sulphur [Sec. 34, T. 9 S., R. 10 W.]					
Surface	2	2	Sand	112	390
Clay	246	248	Clay	2	392
Sand and shale	12	260	Sand	188	580
Sandy shale	18	278	Sandy shale	92	672

TABLE 8.—*Drillers' logs of representative wells in Calcasieu Parish*—Continued

Cu-666. Gulf States Utilities Corp., Lake Charles
[Sec. 9, T. 9 S., R. 9 W.]

Material	Thickness (feet)	Depth (feet)	Material	Thickness (feet)	Depth (feet)
Soil	14	14	Sand, fine	100	990
Sand	8	22	Shale, sandy	280	1,270
Clay, yellow	173	195	Sand, fine	11	1,281
Sand, coarse	25	220	Shale, sticky	219	1,500
Gumbo	100	320	Sand	55	1,555
Sand, good	270	590	Gumbo	38	1,593
Rock, lime	10	600	Sand	27	1,620
Sand, hard	90	690	Shale, sandy	270	1,890
Sand and shale	130	820	Shale, streaky	130	2,020
Shale, sandy	70	890	Gumbo	184	2,204

TABLE 9.—*Wells used in fence diagram*

Fence diagram	Well designation	Location		
		Sec.	Township	Range
1	Cu-625	11	8 S.	13 W.
2	Sun Oil Co	1	8 S.	10 W.
3	Cu-216	18	7 S.	10 W.
4	Union Sulphur Co	34	7 S.	10 W.
5	Shell Oil Co	6	8 S.	9 W.
6	Union Sulphur Co	32	7 S.	7 W.
7	Continental Oil Co	30	7 S.	6 W.
8	Humble Oil Co	19	6 S.	9 W.
9	Placid Oil Co	20	9 S.	7 W.
10	Cu-587	31	9 S.	8 W.
11	Cu-92	34	9 S.	9 W.
12	Cu-653	11	9 S.	10 W.
13	Union Prod. Co	21	8 S.	10 W.
14	Union Sulphur Co	30	9 S.	10 W.
15	Gulf Ref. Co	19	9 S.	11 W.
16	Jefferson Lake Sulphur Co	19	9 S.	12 W.
17	Sexton Oil Co	18	10 S.	12 W.
18	Ohio Oil Co	20	11 S.	13 W.
19	Magnolia Petroleum Co	1	12 S.	12 W.
20	Union Sulphur Co	21	11 S.	10 W.
21	Stanolind Oil and Gas Co	17	11 S.	9 W.
22	Hankamer Ins. Co	32	10 S.	9 W.
23	Cu-446	18	10 S.	9 W.
24	Shell Oil Co	16	11 S.	8 W.
25	Cu-493 and Cu-151	29	10 S.	7 W.
26	Sohio Oil Co	30	10 S.	6 W.
27	Cu-655	34	9 S.	10 W.

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JOHNSTON, O.C. AND GREENE, C.J., 1979

INVESTIGATION OF ARTIFICIAL PENETRATIONS IN THE VINCINITY OF SUBSURFACE DISPOSAL WELLS

INVESTIGATION OF ARTIFICIAL PENETRATIONS IN THE VICINITY OF SUBSURFACE DISPOSAL WELLS

Technical Report

By

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Texas Department of Water Resources

1979

ABSTRACT

The distance to which artificial penetrations should be reviewed in the vicinity of an injection well is dependent upon many variables including the hydrologic and geologic characteristics of the disposal zone, wastewater properties, injection rates and volumes, amount of separation between the base of fresh water and disposal zone, and other disposal operations utilizing the same interval. The Texas Department of Water Resources uses a 2½-mile radius of investigation as a rule of thumb for evaluating applications for waste disposal well permits; however, this distance can be adjusted if reservoir pressure resulting from well injection calculated using the nonequilibrium formula developed by Theis (1935) warrants. Recommendations to reenter and plug abandoned wells were made when pressure calculations indicated injection well operation might create a hazard in improperly plugged wells.

One method of establishing a uniform radius of investigation is the evaluation of disposal zone models. The models demonstrate the sensitivity of the radius of investigation to changes in different reservoir, fluid and injection variables. Since evaluations of artificial penetrations are made prior to drilling a disposal well, it is sometimes difficult to obtain accurate data for the variables affecting reservoir pressure. The investigation of a 2½-mile radius should be continued unless prior justification of a smaller radius is supported by reliable reservoir data. Injection operations should be reevaluated using the data obtained from reservoir testing after well completion.

INTRODUCTION

The Texas Department of Water Resources (TDWR) is the permitting agency for underground injection of industrial wastewater in Texas. One of the aspects of evaluating the suitability of a subsurface disposal project is the investigation of artificial penetrations in the vicinity of a proposed injection well. The distance to which abandoned or completed wells should be reviewed depends upon may variables, including the hydrologic and geologic characteristics of the disposal zone, wastewater properties, injection rate and volumes, amount of separation between base of fresh water and disposal zone, and other disposal operations utilizing the same interval.

The TDWR uses a 2½-mile radius of investigation as a rule of thumb. If reservoir pressure calculations indicate a significant pressure increase at 2½-miles, it may be determined that a greater area of review is necessary. Initially, all applicants must submit data on all known penetrations within a 2½-mile radius of investigation, unless prior justification for a smaller area of review is made. Additional data can be required if the reservoir pressure calculations warrant.

The determination of what constitutes an improperly completed plugged well is a difficult problem. Generally, a well that has been properly completed or abandoned is one where interformational transfer of fluids does not occur or will not occur as a result of changes in the reservoir pressure. Although our primary concern is protection of groundwater resources, oil and gas formations and other mineral bearing zones (i.e., magnesium produced from brines in the Yates Formation) should be protected.

The evaluation of a well must consider the regional geology, completion or plugging methods, and expected reservoir conditions. Most dry exploratory (oil wells) holes on the coastal plain were abandoned with surface casting set and cemented at the base of fresh water and long string casting was usually pulled. Cement plugs were set at the base of the surface casing and at the surface with drilling mud left in the hole in most wells. Due to the unconsolidated nature of the sediments and the plastic nature of most Tertiary shales, abandoned well bores probably do not remain open for long periods of time; however, for the technical evaluations of aquifer penetrations, the holes are assumed to remain open.

In the west and north-central part of the State injection zones, confining beds and most of the overburden strata are more competent, indurated rocks. Well bores will remain open for indefinite periods of time, and frequently drilling fluids and cement may not be in the well bore because of lost circulation zones.

Probably the greatest danger from artificial penetrations occurs in the West Texas area. Most reports of flowing abandoned wells or groundwater contamination from oil field brines are from this area. There are several possible causes for these problems including well bores that do not collapse around the casing or close after casing is removed, or lost circulation zones that force operators to unintentionally abandon or complete a well without adequate mud or cement.

Another problem common to all areas of the State is wells that are temporarily abandoned with casing in the hole and then forgotten. Often erroneous data is submitted on plugging or completion reports. For example, many tabulations indicate that a well is producing; however, the well may not have produced in may years and is temporarily abandoned.

METHOD OF EVALUATION

The staff evaluation of artificial penetrations primarily consists of review of the completion and/or plugging records in the subject area to identify improperly completed or abandoned wells. The pressure increase caused by the proposed injection program is calculated for each potential problem well using estimated values for transmissivity and storage in the nonequilibrium formula developed by Theis (1935). Multiple well and image well effects are considered where applicable. The nonequilibrium formula in United States Geological Survey units is expressed as:

$$\Delta h = \frac{114.6Q}{T} \int_{\frac{1.87r^2 S}{Tt}}^{\infty} \frac{e^{-u}}{u} du$$

Where:

$$U = \frac{1.87r^2 S}{Tt}$$

Δh = change in head at observation point (feet)
Q = discharge of well (gallons per minute)
T = transmissivity (gallons per day per foot)
r = distance to observation point (feet)
S = storage coefficient (dimensionless)
t = time (days)

The nonequilibrium formula is based on the following assumptions:

1) the aquifer is homogeneous and isotropic
2) the aquifer is of infinite areal extent and constant thickness
3) the discharging (injecting) well has a small diameter and completely penetrates the aquifer
4) water is released instantaneously from storage

Although no aquifer exists in nature that meets all of these assumptions, the nonequilibrium formula can be applied successfully to estimate pressure changes. The nonequilibrium formula was modified by Wenzel (1942) as follows:

$$\Delta h = \frac{114.6Q}{T} W(u)$$

Where W (u) represents the "well function of u" and other terms are as previously defined.

$$\int_{\frac{1.87r^2 S}{Tt}}^{\infty} \frac{e^{-u}}{u} = W(u) = -0.577216 = \log_e u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \frac{u^4}{4.4!}$$

Values for W (u) for values of u from 10^{-15} to 9.9 were tabulated by Wenzel (1942).

The formula for obtaining u, as previously stated, is:

$$u = \frac{1.87r^2 S}{Tt}$$

To solve the above equations and estimate pressure increases (Δh), the storage coefficient must be determined. The storage coefficient is the volume of water that is released or taken into storage per unit surface area of an aquifer per unit change in the component of head, normal to that surface. The formula for the coefficient of storage is:

$$S = f(w)\, Ø\, m \left(B + \frac{a}{Ø}\right) \text{ (modified after Jacob (1950))}$$

Where

- f(w) = weight of 1 cubic inch of formation water at stated temperature (pounds)
- Ø = porosity
- m = thickness of saturated aquifer (inches)
- a = 1/bulk modulus of compression of aquifer skeleton (square inches per pound)
- B = 1/bulk modulus of compression of aquifer water (square inches per pound)

REVIEW OF WASTE DISPOSAL WELL FILES

A review of TDWR Staff Technical Reports written during the evaluation of Industrial Waste Disposal Well Applications Nos. WDW-33 through WDW-151 was conducted to determine the distances from injection wells at which improperly abandoned or completed wells have previously posed a hazard to freshwater resources. The scope of this review is limited to those wells described in the Technical Reports as potential problems. An evaluation of the artificial penetrations in the vicinity of many of the earlier permitted wells should be made using real values for reservoir conditions and pressures resulting from many years of injection.

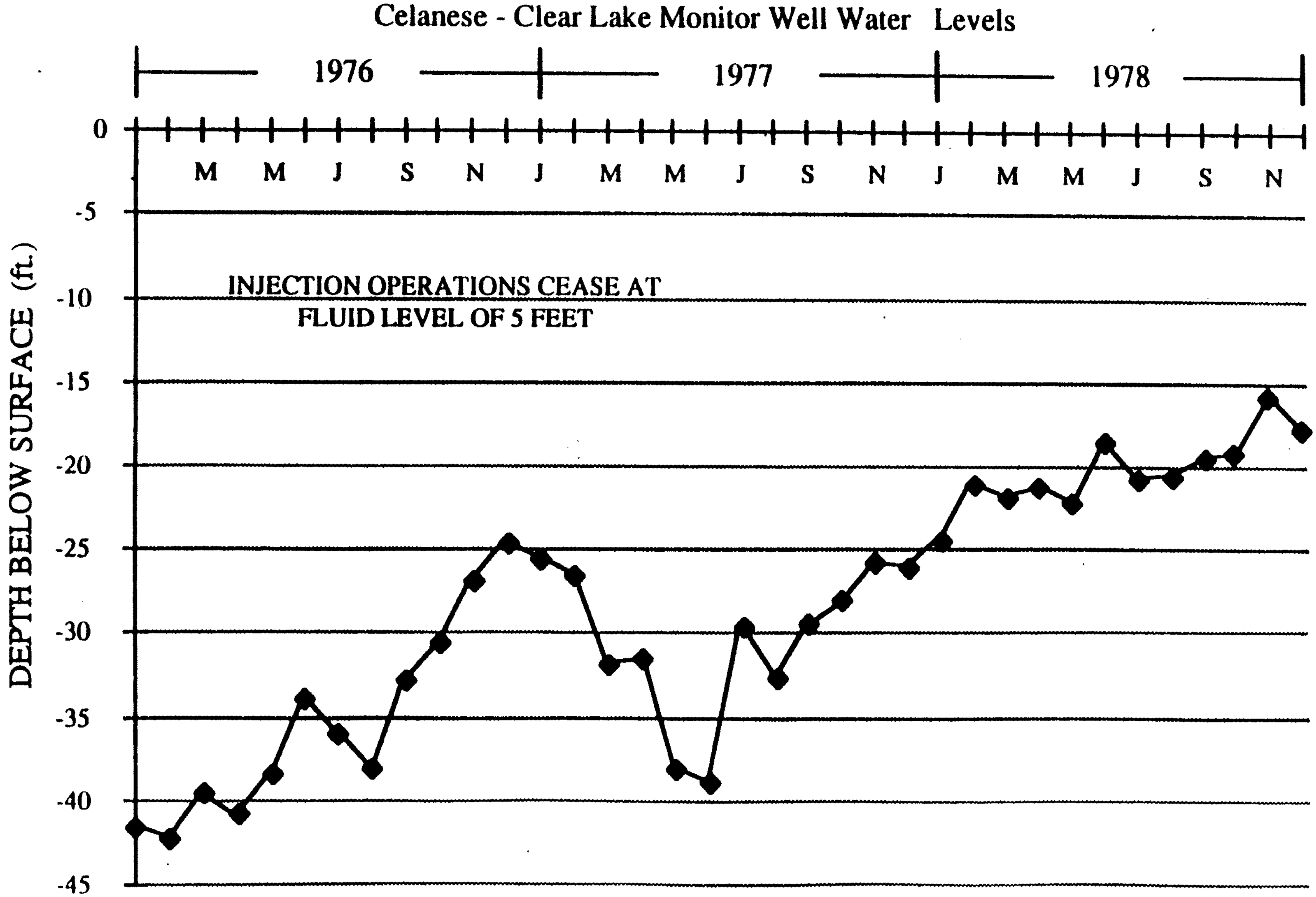
Recommendations to reenter and plug an improperly plugged well or to install a monitor well were made when the calculated increase in pressure at a potential problem well was predicted to be sufficient to cause fluids to migrate up the well bore of the problem well from the injection zone to the base of freshwater. If pressure calculations indicated that the injection well operation would not result in a significant increase in pressure at an improperly plugged well, plugging or monitoring was not recommended.

If pressure calculations indicated a potential hazard where plugging was not practicable. a pressure monitor well was installed and a provision in the permit required the permittee to cease injection operations and recomplete in another zone or plug and abandon the disposal well when reservoir pressures approached a critical level as indicated by the pressure in the monitor well. This approach was taken with Celanese Chemical Company's disposal wells which are located near the Clear Lake Oil Field where twenty producing wells were completed with insufficient surface casing. A graph of the pressure increase since 1976 is shown in Figure 1.

Of the files on 91 waste disposal wells reviewed, 39 Technical Reports described a total of 58 wells considered to be potential problems (not counting the 20 producing wells with insufficient surface casing near Celanese Chemical Company). Plugging or monitoring was recommended in the Technical Reports for 25 improperly completed or abandoned wells at distances ranging from 250 to 16,400 feet from the injection well. Calculations of pressure increase indicated that the injection operations would not create a hazard in 33 of the potential problem wells evaluated at distances ranging from 2,800 feet to 14,500 feet. These figures are listed in Table 1 and represented graphically in Figure 2.

This review suggests that no standard radius of investigation of artificial penetrations can be applicable to all proposed subsurface disposal projects. The distance from an artificial penetration to the injection well is only one of many variables controlling the pressure increase as a result of injection operations. For example, a recommendation to plug or monitor an unplugged well 16,400 feet from a proposed injection well in Harris County was made due to an injection rate of 1,650 gpm (WDW-89 and WDW-90) with nearby injection wells utilizing or permitted to utilize the same interval (Ethyl Corp. Permit No. WDW-86 @ 1000 gpm). Conversely, pressure calculations indicated no hazard for an unplugged well 2,800 feet from a proposed injection well in Nueces County (WDW-97 and WDW-98) based on an injection rate of 250 gpm with no other injection wells utilizing the same interval. Discussion of the relative significance of the variables affecting pressure increase is necessary to determine the distance from a proposed injection well at which artificial penetrations should be evaluated.

Figure 1



Celanese - Clear Lake Monitor Well Water Levels
1976
1977
1978
M M J S N J M M J S N J M M J S N
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
DEPTH BELOW SURFACE (ft.)
INJECTION OPERATIONS CEASE AT
FLUID LEVEL OF 5 FEET

Table 1. Evaluation of Petential Problem Well Recommendations
Waste Disposal Well Permit Nos. WDW-33 to WDW-151

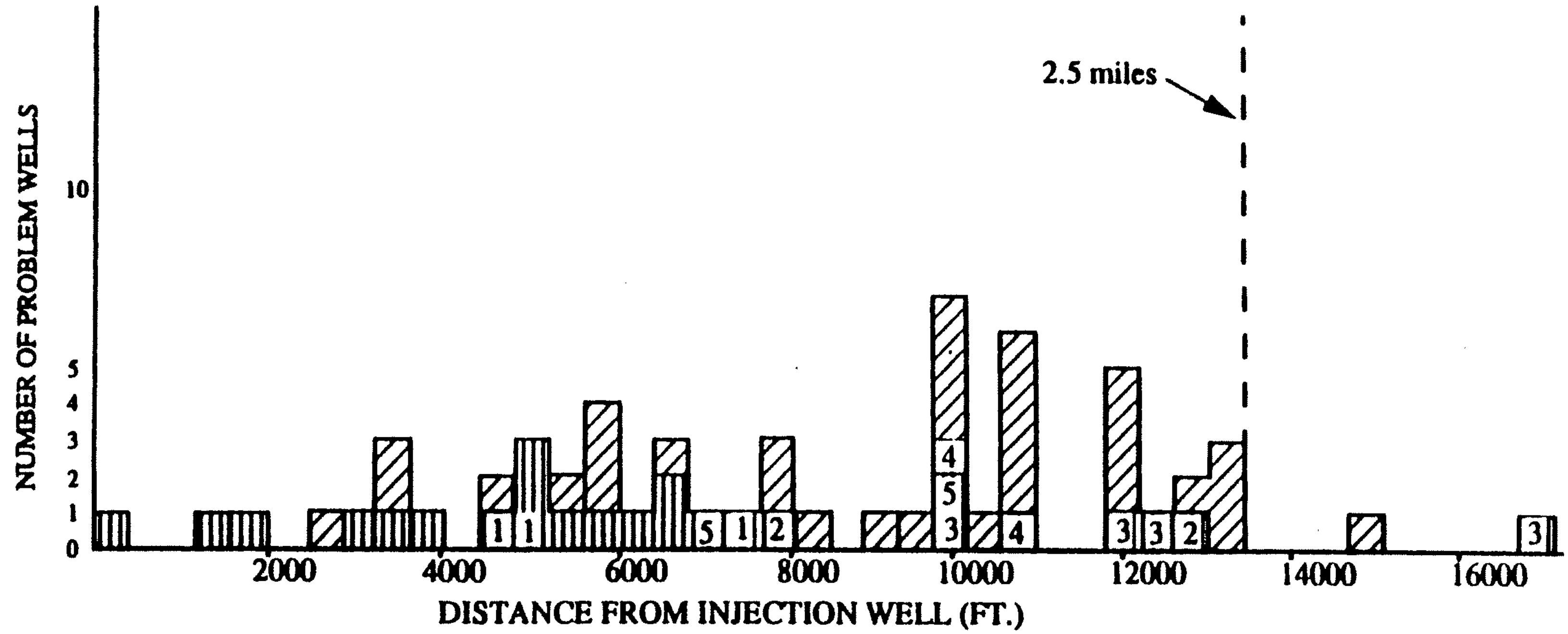
WDW No.	No. of Wells	Distance (feet)	Recommendatio.
33, 45, 69*	20	7,920 to 13,200	monitor
34,113,114	4	10,200, 13,200 & 2 @ 12,000	$\Delta\rho$ calc no hazard
51	2	10,000, 10,560	$\Delta\rho$ calc no hazard
59, 71, 99		10,000, 10,560	plug or monitor
49	1	12,000	$\Delta\rho$ calc no hazard
70	2	11,800, 12,500	$\Delta\rho$ calc no hazard
73	2	5,400, 7,800	$\Delta\rho$ calc no hazard
78	2	3,000, 4,000	plug or monitor
78	3	5,900 to 6,000	$\Delta\rho$ calc no hazard
80, 127, 128	1	10,800	no hazard
80, 127, 128	1	12,700	plug
82, 83	1	8,000	$\Delta\rho$ calc no hazard
82, 83	1	4,900	plug or monitor
86**	4	1,900, 4,500, 5,000, 7,280	plug or monitor
89 & 90***		10,000, 12,000, 12,400, 16,400	plug or monitor
89 & 90	1	14,500	$\Delta\rho$ calc no hazard
91	1	7,920	plug or monitor
92	1	250	plug
97, 98	5	2,800, 6,700, 13,000 & 2 @ 13,200	$\Delta\rho$ calc no hazard
103	1	9,000	$\Delta\rho$ calc no hazard
105	1	9,500	$\Delta\rho$ calc no hazard
110	2	10,000	$\Delta\rho$ calc no hazard
111	2	3,300	$\Delta\rho$ calc no ha[illegible]
119	1	10,500	$\Delta\rho$ calc no h[illegible]
123, 124	1	3,600	plug or monitor
126	2	@ 10,500	$\Delta\rho$ calc no hazard
130	4	5,800, 6,500, 6,900 & 9,900	plug or monitor
133	1	1,320	plug or monitor
139	3	4,800, 2 @ 10,000	$\Delta\rho$ calc no hazard
140	1	5,000	plug or monitor
141	2	5,500, 6,500	plug or monitor

* Celanese Chemical Co. disposal wells are located near the Clear Lake Oil Field where some producing wells have short surface casing.

** 1,000 gpm

*** 1,650 gpm

Figure 2



Plug or Monitor Well Recommended

Δ_p Calculation No Hazard

Initial Review No Hazard
Plug or Monitor Well Recommended Later

1 - WDW 86 1000 gpm
2 - British - American UT B - 1 Plugged by Monsanto & Amoco
3 - WDW 89, 90 1650 gpm
4 - WDW 51 No Hazard; WDW 59, 71 99 - plug or monitor
5 - WDW 130 monitor

DISPOSAL ZONE MODELS

Establishing uniform regulations for a reasonable radius of investigation of artificial penetrations around injection wells is a complex problem due to the many variables that affect pressure. Models of disposal zones have been developed in an attempt to quantify the effects of some of these variables. The relative significance of the values assumed for these variables with respect to reservoir pressure can be assessed in this manner.

ASSUMPTIONS

A primary concern in the preliminary evaluation of a subsurface injection program is to insure that sufficient area around the disposal well is investigated; therefore, parameters required for the determination of the radius at investigation were selected which would result in a conservative analysis. The reservoir, fluid, and injection characteristics assumed for a general analysis are as follows:

1.	porosity	.10 to .30 (percent)
2.	permeability/viscosity ratios	10 to 400 milidarcies/ centipoise (md/cp)
3.	thickness	100 feet
4.	depth of injection zone	5.000 to 7.000 feet
5.	rock compressibility	4.8×10^{-6} to 3.2×10^{-6} psi^{-1}
6.	water compressibility	3.0×10^{-6} psi^{-1}
7.	fluid density (unplugged well bore)	9.0 lb/gal
8.	initial reservoir pressure gradient	.45 psi/ft.
9.	fracture gradient	.65 psi/ft.
10.	maximum injection rates	$\leq$350 gpm (gallons per minute)
11.	project life	25 years

CALCULATION

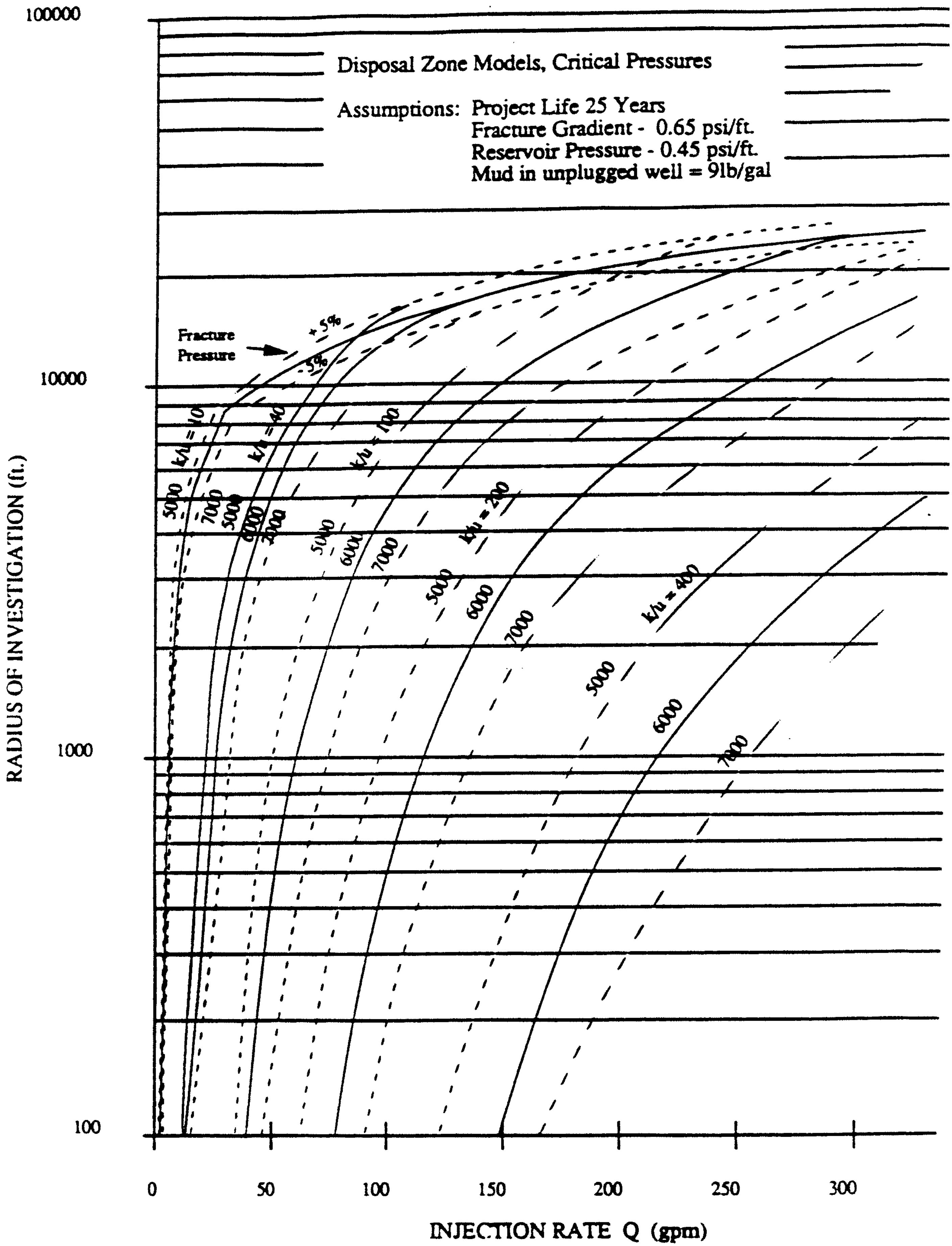
The increase in reservoir pressure resulting from 25 years of injection operations is estimated from the Theis non-equilibrium formula. The critical pressure shown on Figure 3 is the pressure required to displace 9 lb/gal mud in an unplugged well bore. These values are determined at various distances for three assumed depths (5,000, 6,000, and 7,000 feet) and five assumed permeability/viscosity ratios (10, 40, 100, 200, and 400 md/cp). Bottom hole pressure in the injection well is calculated assuming a fluid density of 30-40,000 ppm TDS (specific gravity of 1.04) and the bottom hole pressure in the unplugged well bore is calculated assuming a 9 lb/gal mud is left in the well (specific gravity of 1.085). The data is also plotted for porosity ranging from .10 to .30 and rock compressibility ranging from 4.8 x 10^{-6} psi/lb. A net sand thickness of 100 feet was assumed and various injection rates up to 350 gpm were used.

The maximum injection rate was determined that would not result in reservoir pressure exceeding the fracture pressure and is indicated on Figure 3. The fracture gradient was assumed to be .65 psi/ft and Figure 4 is a graph of the effect of ±5% error in the fracture gradient. Figure 5 is a graph of the effect of an error of ±2% in the initial reservoir pressure estimation.

LIMITATIONS

The limitations of a conservative nature of the disposal zone models presented include: no allowance for friction loss or skin effects, assuming constant injection rates and pressure for 25 years, constant (100 ft) thickness, assuming well bore of improperly plugged well remains open, and assuming hydrologic communication with improperly plugged well. Other limitations include the assumptions of: homogeneous isotropic media, compatibility.

Figure 3



Disposal Zone Models, Critical Pressures
Assumptions: Project Life 25 Years
Fracture Gradient - 0.65 psi/ft.
Reservoir Pressure - 0.45 psi/ft.
Mud in unplugged well = 9lb/gal
Fracture Pressure
+5%
-5%
k/u = 10
k/u = 40
k/u = 100
k/u = 200
k/u = 400
5000
6000
7000
100000
10000
1000
100
RADIUS OF INVESTIGATION (ft.)
0
50
100
150
200
250
300
INJECTION RATE Q (gpm)

Sensitivity of Calculated Radius of Investigation
to Change of Fracture Gradient of ± 5%

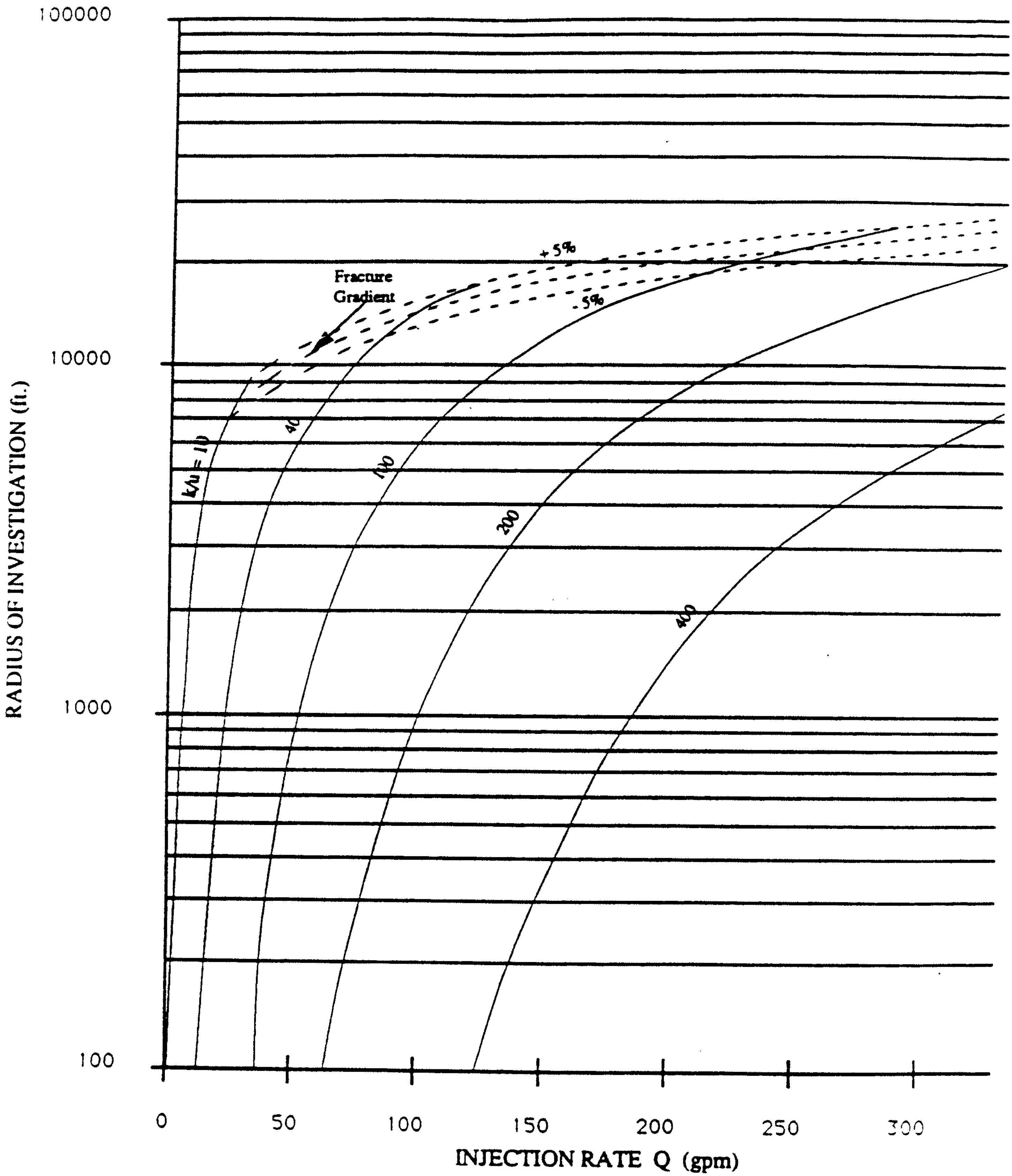
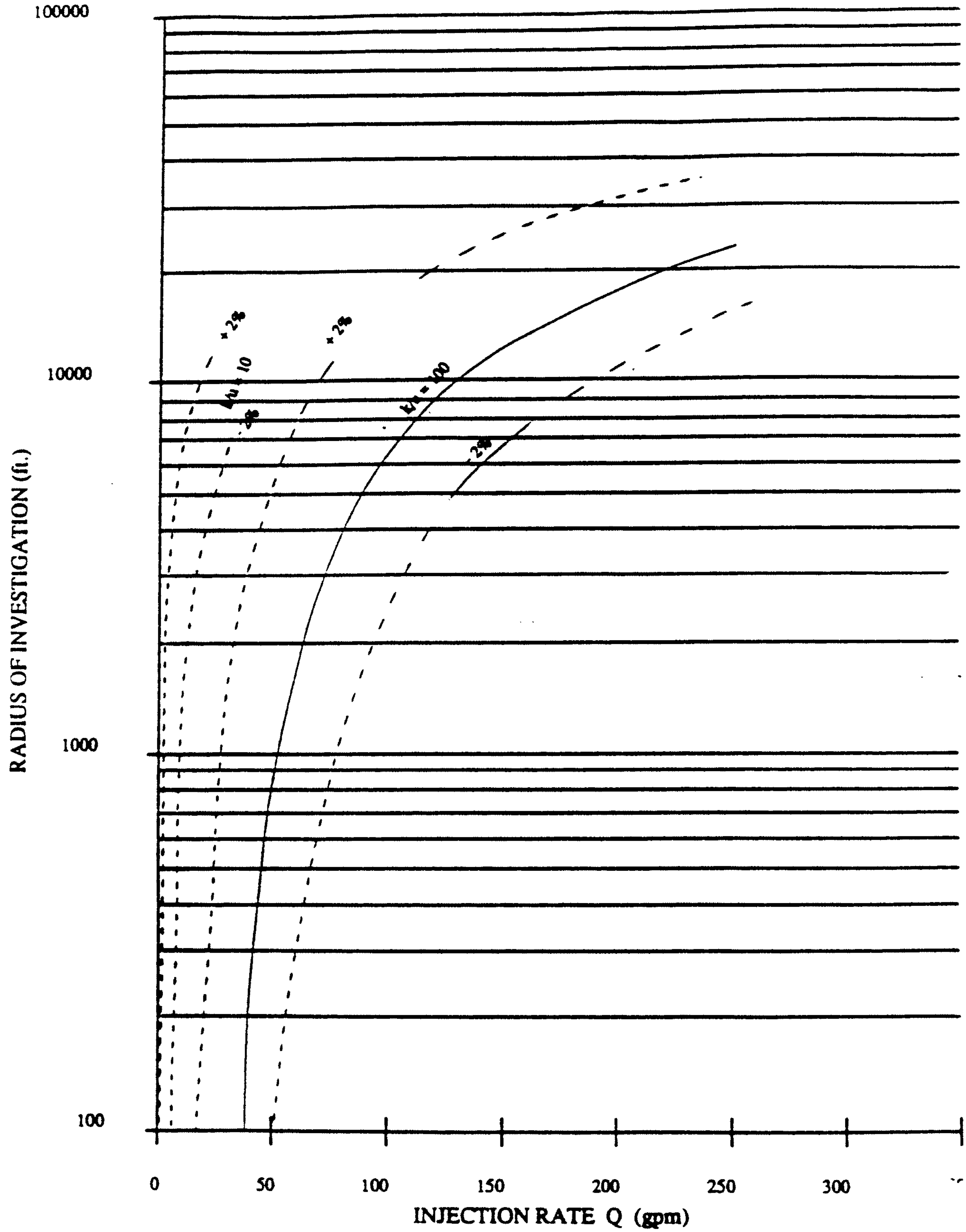


Figure 5

Sensitivity of Calculated Radius of Investigation
to Change of Fracture Gradient of ± 5%



CONCLUSIONS

The review of TDWR Staff Technical Reports prepared during the evaluation of waste disposal well applications indicated that the recommendations as to potential hazards of artificial penetrations were not strictly distance-related. Generally, more recommendations to plug abandoned wells were made for the closer wells evaluated, however, the exceptions show the significance of the assumed values for reservoir, fluid, and injection factors.

The disposal zones models demonstrated the relative significance of the reservoir, fluid and injection variables with respect to areal influence of well injection. The principal factors affecting reservoir pressure increase resulting from well injection appear to be: injection rate, thickness, initial reservoir pressure, permeability/viscosity ratios, method of plugging or completion of investigated wells, and depth of disposal zone. These models emphasize the necessity of obtaining accurate reservoir data for evaluation of pressure increases.

This report only scratches the surface of the possible applications of disposal zone models to predict pressure increases due to well injection. This approach should be very useful in evaluating salt water disposal projects associated with oil and gas production. The data developed from the disposal zone models indicates that the current practice of investigating artificial penetration within a 2½-mile radius around proposed industrial waste disposal wells should be continued, unless justification based on reliable reservoir data indicated otherwise. The modification of the disposal zone models to fit specific injection well sites should be considered, where applicable. Reevaluation of the radius of significant pressure increase should be examined when the reservoir data becomes available after well completion.

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Parameter Units	Time Days	Q gpm	Ø %	a psi/lb	B psi/lb	S	k/u md/cp	ρ ratio	Depth ft.	Radius ft.	Δp psi	Δp + BHP psi
									7000	10	321	3470
										1800	140	3290
		30								10	1040	2390
										9000	104	2350
		35							6000	10	1219	3919
										9000	122	2820
									7000	10	1393	4543
										9000	140	3290
		50	.30	$3.2X10^{-6}$	$3x10^{-6}$	.000185	100	1.04	5000	10	200	2450
										750	100	2350
									7000	10	200	3350
										130	141	3290
		250							5000	10	1005	3250
										25000	100	2350
		350							7000	10	1407	4556
										25000	141	3290
	9125	263	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	100	1.04	5000	10	1045	
										16000	145	
		200								10700	145	
		100								2200	145	
		50								100	145	
		241								10	955	
		1100								35000	55	
		200								31000	55	
		100								16000	55	
		50								4800	55	
		25								450	55	
	9125	111.5	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	40	1.04	5000	10	104[illegible]	
										10800	145	
		100								9400	145	
		50								2600	145	
		35								1400	145	
		25								225	145	
		102								10	955	
										23000	55	

Parameter Units	Time Days	Q gpm	Ø %	a psi/lb	B psi/lb	S	k/u md/cp	ρ ratio	Depth ft.	Radius ft.	Δp psi	Δp + BHP psi
		60								15000	55	
		30								6600	55	
	9125	50	.10	4.8×10^{-6}	3×10^{-6}	.00023	10	1.04	5000	10	1716	
		30.5								10	1046	
										6000	144	
		20								3400	145	
		10								700	145	
		27.8								10	955	
										12000	55	
										9800	55	
		10								5000	55	

APPENDIX

Parameter Units	Time Days	Q gpm	Ø %	a psi/lb	B psi/lb	S	k/u md/cp	ρ ratio	Depth ft.	Radius ft.	Δp psi	Δp + BHP psi
	9125	50	.10	$4.8x10^{-6}$	$3x10^{-6}$	.00023	10	1.04	5000	10	1716	3966
		30								10	1030	3280
										8000	105	2355
		50							6000	10	1716	4540
		35								10	1201	3900
										8000	123	2353
		50							7000	10	1716	4870
		40								10	1375	4525
										8000	141	3290
	9125	50	.10	$4.8x10^{-6}$	$3x10^{-6}$	.00023	40	1.04	5000	10	470	2820
										5500	103	2250
									6000	10	470	3170
										4000	121	2821
									7000	10	470	3620
										3000	137	3287
		100							5000	10	940	3190
										14000	102	2350
									6000	10	940	3640
										12000	118	3288
									7000	10	940	4090
										10000	138	3290
		105							5000	10	985	3235
										15000	100	2350
		130							6000	10	1200	3920
										15000	123	2920
		150							7000	10	1408	4560
										15000	142	3292
		50	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	100	1.04	5000	10	198	2450
										750	98	2350
									6000	10	198	2900
										300	120	2820
									7000	10	198	3350
										100	140	3290

Parameter Units	Time Days	Q gpm	Ø %	a psi/lb	B psi/lb	S	k/u md/cp	ρ ratio	Depth ft.	Radius ft.	Δp psi	Δp + BHP psi
	9125	100	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	100	1.04	5000	10	397	2650
										6000	99	2350
									6000	10	397	3100
										4000	120	2820
									7000	10	397	3550
										2500	140	3290
		200							5000	10	793	3050
										18000	100	2350
									6000	10	793	3500
										14000	121	2820
									7000	10	793	3950
										11000	140	3290
		252							5000	10	1000	3250
										23000	100	2350
		300							6000	10	1200	3900
										22500	120	2820
									7000	10	1400	4550
										22500	140	3290
	9125	200	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	200	1.04	5000	10	410	2660
										8000	100	2350
									6000	10	410	3100
										5500	120	2820
									7000	10	410	3560
										3500	140	4550
		300							5000	10	619	2870
										17000	100	2350
									6000	10	619	3320
										13000	120	2820
									7000	10	619	3770
										10000	140	3290
	9125	300	.10	$4.8X10^{-6}$	$3x10^{-6}$	.00023	400	1.04	5000	10	321	2570
										5500	100	2350
									6000	10	321	3020
										3200	120	28

APPENDIX

CALCULATIONS

Fracture Pressures ±5%

Frac. press. = formation breakdown pr.
p = Frac press - bottom hole pressure

Depth (feet)	-5% Frac. Press.	p	Frac. Press.	p	+5% Frac. Press.	p
5000	3090	840	3250	1000	3410	116
6000	3705	1005	3900	1200	4100	140
7000	4325	1175	4550	1400	4780	160

Formation Fluid Density ±2%

Depth	-2%		Depth	+2%	
5000	2205	145	2350	100	2295
6000			2800	120	
7000			3290	140	

ASSUMPTIONS

d = 100 ft.
t = 9125 days
Q = 350 gpm
Ø = 0.1 to 0.3
a = 4.8×10^{-6} to 3.2×10^{-6} psi^{-1}
B = 3×10^{-6} psi^{-1}
k/u = 10, 40, 100, 200, 400 md/cp
ρ = 1.04 (Formation Fluid)

depth = 5000, 6000, 7000 feet
frac. gradient = 0.65 psi/ft.
frac. pressure = 3250, 3900, 4550 psi
mud density = 9 lb/gal
specific gravity (mud) = 1.085
bottom hole pressure (unplugged well) 2350, 2820, 3290 psi
specific gravity (water) = 1.04
bottom hole pressure = 2250, 2700, 3000 (injector)

$$\Delta h = \frac{1146.Q}{T} W(u)$$

$$U = \frac{1.87 r^2 S}{Tt}$$

Where:

Δh = change in head (feet)
Q = discharge (gpm)
T = Transmissivity (gpd/ft)
W(u) = well function of
r = radius from injection well (feet)
t = time since injection began (days)
S = storage coefficent

$$S = F(w) \, \varnothing \, m \left(B + \frac{a}{\varnothing} \right)$$

Where:

F(w) = formation factor
$\varnothing$ = porosity (percent)
m = thickness of aquifer (inches)
B = compressibility of water psi/lb
a = compressibility of aquifer skeleton psi/lb

JONES, T.A. AND HAIMSON, J.S., 1986

DEMONSTRATION OF CONFINEMENT:

AN ASSESSMENT OF CLASS I WELLS IN THE GREAT LAKES AND GULF COAST REGIONS

DEMONSTRATION OF CONFINEMENT: AN ASSESSMENT OF CLASS I WELLS IN THE GREAT LAKES REGION AND GULF COAST REGIONS

FUNDED BY:
AMERICAN CYANAMID COMPANY
BETHLEHEM STEEL CORPORATION
DETROIT COKE CORPORATION
ETHYL CORPORATION
GOLDEN STRATASERVICES, INC.
INLAND STEEL COMPANY
LTV STEEL COMPANY

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ABSTRACT

An evaluation of geologic confinement with respect to Class I injection wells was performed for the Gulf Coast and Great Lakes Region to specifically address portions of the Hazardous and Solid Waste Amendments (HSWA) of 1984 which require the demonstration that underground injection of hazardous waste is protective of human health and the environment.

Two representative examples of actual confinement systems were selected from each region and evaluated in terms of physical characteristics and the potential for upward migration of injected fluids above the confinement system. An in-depth review of lithology, stratigraphy, and reservoir properties demonstrated the ability of the geologic confinement systems to allow no vertical migration of injected waste over long time periods.

A "confinement system" rather than confining layer concept has been introduced that demonstrates the effectiveness of low permeability lithologic layers interbedded with relatively higher permeability units to trap and isolate waste from the assessible environment.

Circumvention of confinement and the need for additional monitoring of Class I well facilities was evaluated by reviewing the potential pathways for upward fluid movement and relevant mechanisms for monitoring. The conclusion reached that there is no need for additional monitoring in the form of monitor wells within these particular geologic regions is supported by the following factors:

* Sufficiently thick confining system.
* Absence of problem artificial penetrations.
* Absence of faulting or other complex geologic structures.

A complete review of all confinement issues, mechanisms for failure and present ability to monitor yields the following conclusion: the underground injection of hazardous waste is protective of human health and environment in areas where the geology can be demonstrated to provide adequate confinement and should therefore continue as a disposal practice. The wastewater is isolated from the accessible environment and is confined over geologic time.

INTRODUCTION

The twentieth century is known as a period of rapid growth in industrial technologies resulting in higher demands for natural resources such as oil, gas and minerals. Increased production and consumption has resulted in a larger volume of waste products. This century may very well be remembered not only for its technology but also for the waste disposal practices utilized and their impact on human health and environment. The practice of underground injection to dispose of municipal and industrial wastewater began in the 1950's and continues today under an increasing level of regulatory constraints.

The most recent in a long series of regulatory actions pertaining to underground injection is the 1984 Hazardous and Solid Waste Amendments (HSWA). The HWSA require the Environmental Protection Agency (EPA), inter alia to make a determination by August 8, 1988, regarding the impact to human health and the environment from the disposal of hazardous waste by underground injection see 3004 (f)(2) of RCRA, 42 U.S.C. 6924 (f)(2). Pursuant to this statutory directive, the US EPA may promulgate regulations which will impose a ban on the disposal of such waste by Class I wells if that practice is determined not to be protective of human health and environment as long as the waste remains hazardous. Id. A "hammer provision" is provided in the amendments such that, if the EPA fails to reach a decision for the continuance of present disposal practices, the injection of certain hazardous waste will be prohibited by the specified date in 1988 3004 (f)(3) of RCRA, 42 U.S.C. 1924 (f)(3).

To provide the EPA with a key piece of the information needed to evaluate the future role of Class I wells, a coalition of injection well operators was formed. As a specific objective, this "Class I Coalition" is to examine and supply technical data and information on geologic confinement systems to define the role of monitoring associated with Class I wells. Geologic confinement and monitoring of underground injection via Class I wells are necessities to ensure the continued protection of overlying underground sources of drinking water (USDW). There is no doubt that without geologic confinement, underground injection is not feasible; however, many disagree on "how much confinement is enough?". Historically, three groups have emerged with differing viewpoints on the same environmental concern.

The public wants a guarantee of no environmental risk. This position is understandable given the front page media coverage of hazardous waste cleanups involving pits, ponds, lagoons and landfills. Underground injection is all too often lumped with these other land disposal methods.

On the other hand, scientists who routinely work with the injection, storage and production of fluids in the subsurface environment, judge underground injection in terms of rock properties, pressures and mechanical specifications. Their assessment of the adequacy of confinement focuses upon the evaluation of geologic criteria such as hydrology, stratigraphy, and reservoir mechanics.

The EPA has suggested negotiated rulemaking between these two groups as a method to decide upon the future role of underground injection. On one side the public says that there can never be enough confinement, yet the scientific community says the current level of confinement and monitoring is adequate in maintaining risk at an acceptable low level.

In order to meet the challenges of the HSWA of 1984, this report centers on the demonstration of confinement. An assessment of Class I well confinement systems and monitoring requirements is provided for the Great Lakes and Gulf Coast Regions.

GEOLOGIC CONFINEMENT SYSTEMS

From a historical perspective, much of the published literature regarding underground injection of hazardous waste has been focused on sophisticated technologies for delivering fluid to the receiving formation rather than the geologic confinement necessary to keep it there. Recent comparisons of underground injection to other land disposal techniques where confinement is viewed in terms of liners or layers has resulted in a common misconception. It is that Class I wells have a only single impermeable confining layer located immediately above the injection zone. Figure 1 is a good example of how this view of subsurface geology has been historically presented.

The single confining layer concept associated with Class I wells should be replaced by a more accurate term - a "confinement system". A confinement system is considered to include all the stratigraphic units between the top of the permitted injection zone and the base of the lowermost USDW. Figure 1 is a schematic illustrating this relationship of a confinement system to the injection zone and USDW. Functioning as a series of barriers to prevent vertical migration of injected fluids, a confinement system usually contains a high degree of natural geologic heterogenity. It is multilayered; composed of interbedded impermeable and permeable layers over a wide areal extent.

For the purposes of this discussion, two representative examples of actual confinement systems from the Great Lakes and Gulf Coast Region are presented. These regions were selected because they represent the largest concentration of Class I wells in the United States. The Great Lakes example includes a common injection zone (Mt. Simon Sandstone) and confinement system (Eau Claire Formation) typical of the confinement system in the region.

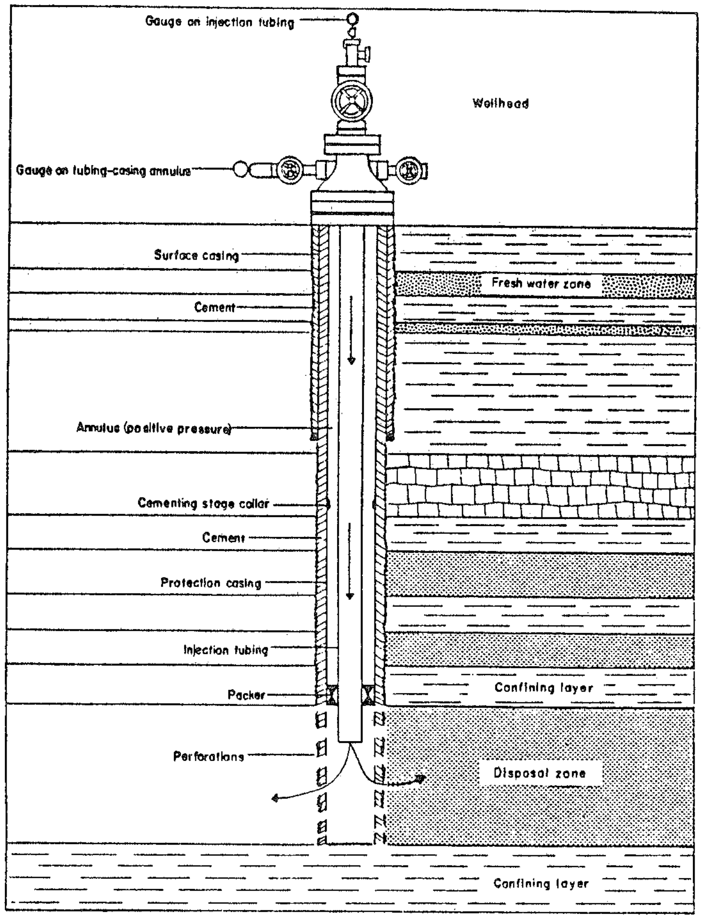
The other example from the Gulf Coast Region is also representative of the reservior and confinement geology and provides a good comparison to the formations of the Great Lakes Region.

EXAMPLE OF GREAT LAKES REGION CONFINEMENT SYSTEM

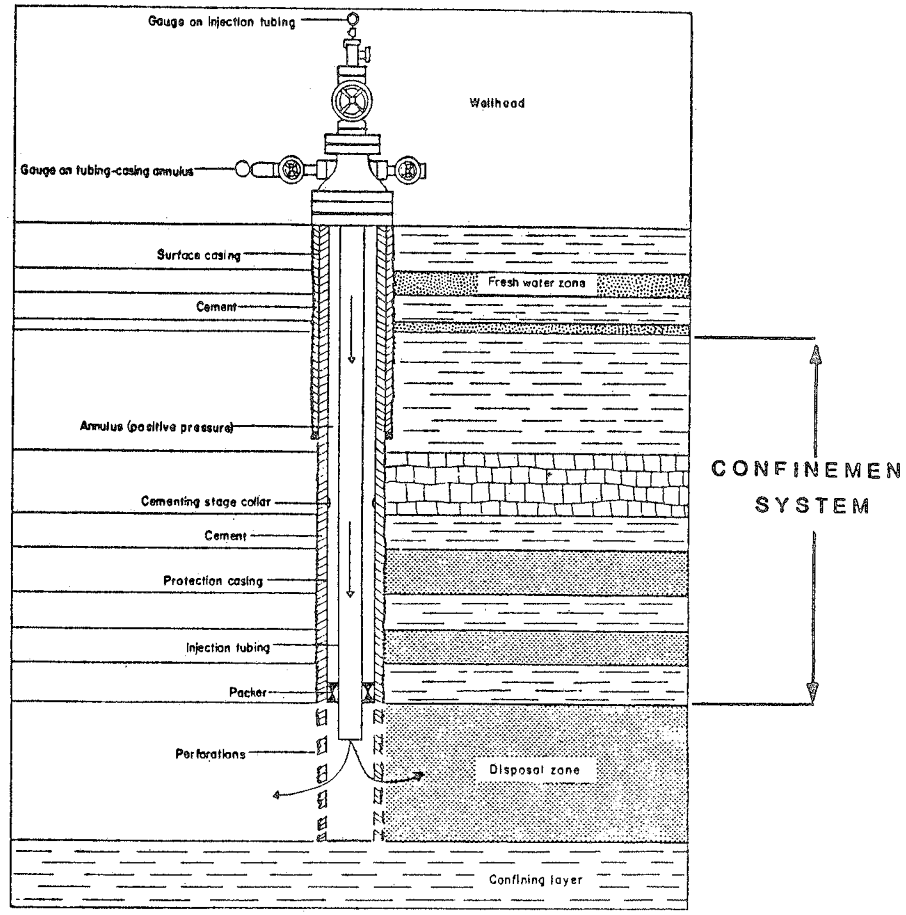
The geologic characteristics of the Great Lakes Region can be broadly generalized due to the relative continuity of the subsurface formations. This is especially true in Illinois, Indiana and western Ohio where the following geologic criteria characterize the region.

1. The Mt. Simon Sandstone is utilized in a large majority of the existing Class I wells it has been widely cited by Don L. Warner, ORSANCO and other publications as an example of a good injection zone due to its depth, thickness, high TDS formation water, and relatively high permeability and porosity values. These Mt. Simon properties are also important to thė evaluation of confinement because they result in low reservoir pressure buildup values, minimizing the upward driving forces.
2. The Eau Claire Formation regionally maintains its confining lithology of shale - siltstone and carbonates, separating the Mt. Simon Sandstone from overlying USDWs.

FIGURE 1 CONCEPTS OF CONFINEMENT: PAST & PRESENT



SINGLE CONFINING LAYER CONCEPT



CONFINEMENT SYSTEM CONCEPT

(modified from TEXAS WATER QUALITY BOARD, 1972)

3. Natural lithologic heterogenity within the Eau Claire itself provides multiple levels of confinement.
4. A very low occurrence of faulting and complex geologic structures due to the tectonically relaxed structural setting.

A type example of the Great Lakes Region confinement system is illustrated in Figure 2. The example was taken from a Class I well in northwest Indiana to illustrate the relationship of the confinement system to the injection zone, USDWs, and other stratigraphic units. In addition, a large amount of full hole core permeability data was available for the confining system at this well. This type of core data is relatively rare for existing wells and allows a much closer and accurate evaluation of the confinement system.

Three geophysical well logs are used to establish lithology and determine the depth relationships of the various geologic units. A gamma ray/neutron log has been reduced in scale so that the stratigraphic position of the confinement system to the injection zone, USDWs and other units can be accurately shown. A gamma ray log measures the natural radioactivity of rock and is most commonly used to determine shale lithologies. When combined with a neutron log, the combination of curves is used to identify bed boundaries and compute thickness. However, the greatly reduced scale of the gamma ray/neutron log is ideal for showing the entire stratigraphic column, its drawback is that it lacks the detail necessary to evaluate the confinement system.

For this reason, the confinement system has been blown up to allow a closer inspection. Two logs are included so that the following individual bed characteristics can be delineated.

<u>Gamma Ray Log</u> - By measuring the natural earth radioactivity, the gamma ray log is used to indicate shale lithologies. The shale percentage and thickness are important since these parameters are fundamental criteria from which confinement systems have been historically evaluated.

<u>Resistivity Log</u> - The resistivity portion of the log measures the resistivity of the rock and water and can be used to establish formation tops and lithologies in addition to shale. In this example, the resistivity curves identify the thin sand beds and the carbonate portions of the Eau Claire.

<u>Microlog</u> - A microlog is a resistivity log that is quite different from the normal resistivity logs. Instead of measuring the formation resistivity several feet away from the wellbore, the microlog reads near wellbore resistivity. During the drilling of a well, areas of appreciable invasion result in deposits of drilling mud on the borehole well as a filter cake. The response of the microlog curves is affected by the mud cake and is frequently used to detect permeable zones. However, in this example, the microlog is used to correlate nonpermeable zones of confinement. So that the permeable and nonpermeable zones are

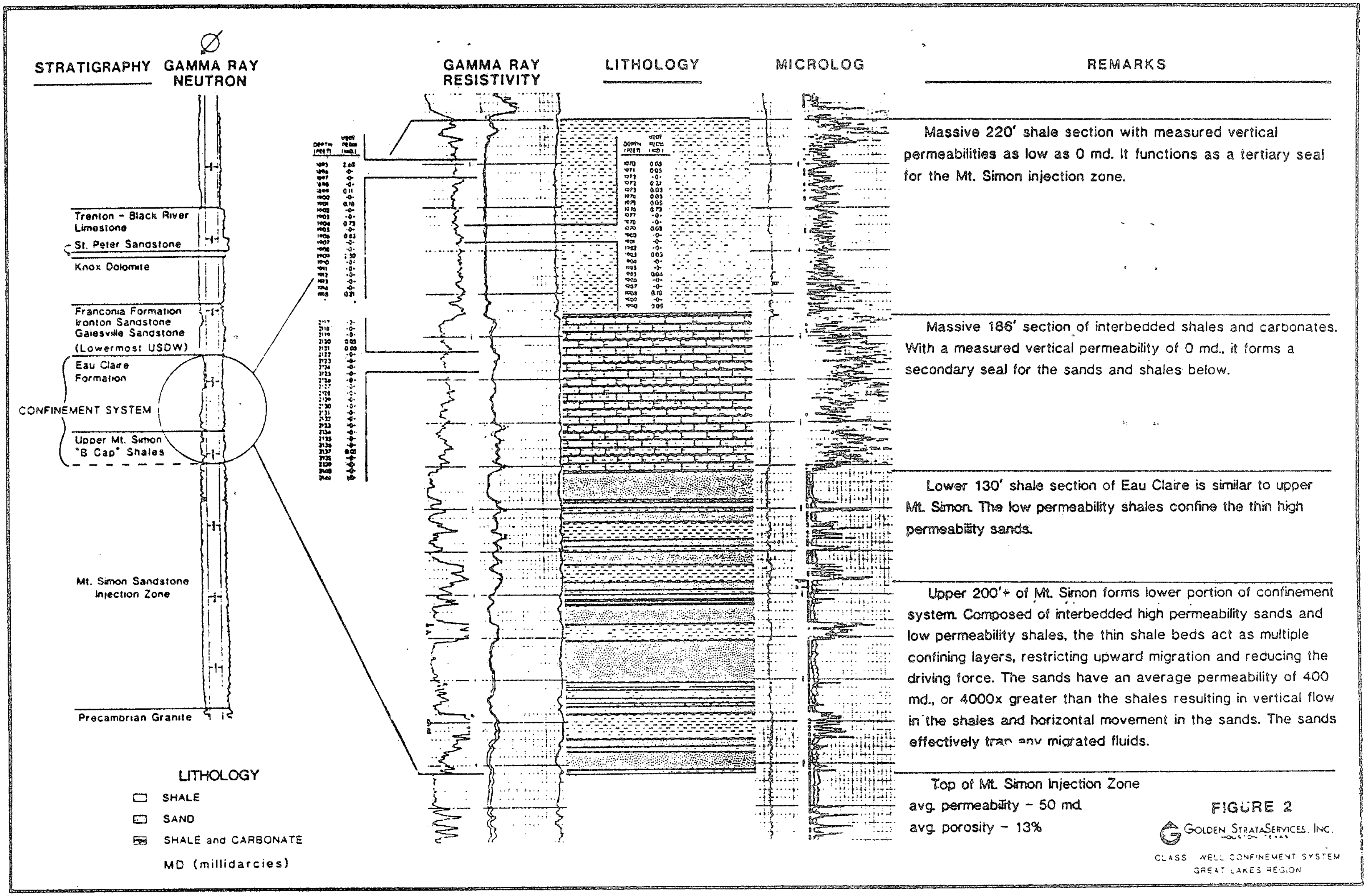

STRATIGRAPHY
Ø
GAMMA RAY
NEUTRON
Trenton - Black River Limestone
St. Peter Sandstone
Knox Dolomite
Franconia Formation
Ironton Sandstone
Galesville Sandstone
(Lowermost USDW)
Eau Claire Formation
CONFINEMENT SYSTEM
Upper Mt. Simon "B Cap" Shales
Mt. Simon Sandstone Injection Zone
Precambrian Granite
GAMMA RAY
RESISTIVITY
LITHOLOGY
MICROLOG
REMARKS
Massive 220' shale section with measured vertical permeabilities as low as 0 md. It functions as a tertiary seal for the Mt. Simon injection zone.
Massive 186' section of interbedded shales and carbonates. With a measured vertical permeability of 0 md., it forms a secondary seal for the sands and shales below.
Lower 130' shale section of Eau Claire is similar to upper Mt. Simon. The low permeability shales confine the thin high permeability sands.
Upper 200'+ of Mt. Simon forms lower portion of confinement system. Composed of interbedded high permeability sands and low permeability shales, the thin shale beds act as multiple confining layers, restricting upward migration and reducing the driving force. The sands have an average permeability of 400 md., or 4000x greater than the shales resulting in vertical flow in the shales and horizontal movement in the sands. The sands effectively trap any migrated fluids.
Top of Mt. Simon Injection Zone
avg. permeability - 50 md
avg. porosity - 13%
LITHOLOGY
SHALE
SAND
SHALE and CARBONATE
MD (millidarcies)
GOLDEN STRATASERVICES, INC.
CLASS WELL CONFINEMENT SYSTEM
GREAT LAKES REGION

FIGURE 2

more easily identified on the microlog, a dark band has been added adjacent to the depth track. Permeable zones are indicated by a dark band with nonpermeable zones having no dark band.

The confinement system not only includes the entire Eau Claire Formation but also the upper portion of the Mt. Simon Sandstone in which the "B Cap" shales are located. The confinement system can be lithologically divided into three distinct units. The lowermost unit immediately overlying the lower Mt. Simon injection zone is composed of an alternating sequence of permeable sands and impermeable shales. The second or middle confinement unit is a thick section of thinly laminated shale and carbonate with measured vertical permeabilities values of zero. The upper unit which is directly below the lowermost USDW in northwest Indiana is a very massive section of dense, low permeability shale.

Lower Confinement Unit - Composed of 200' of the upper Mt. Simon and the lower 130' of the Eau Claire, this section is characterized by the numerous interbedded sands and shales. Although not shown on Figure 2, fullhole core permeability data from an adjacent injection well provide the permeability relationship of the individual beds. The thin shales have a vertical permeability that is less than 1.0 md generally falling in the 0.1 to 0.5 md range. A rapid change in vertical permeability is experienced as the transition of shale to sand occurs. The sands have high permeabilities ranging from 100 md to over 900 md with an average of 400 md. Since the sands have a relative permeability that is 4000x greater than the shales, any migration of fluids will be vertical through the shales and horizontal in the sands. The shales reduce the upward driving force through their inherent frictional resistance to flow. Any residual pressure or fluid would be dissipated by the first sand unit halting upward migration. In this manner, the lower confinement unit alone is effective in halting any upward migration. The repeating sequence of sands and shales form multiple layers of protection within the low confinement unit.

Middle Confinement Unit - The massive 186' section of thinly laminated shales and carbonates is best seen from the microlog. Although this section appears similar to the lower sequence of sands and shales of the gamma ray resistivity log, the microlog response is quite different. The numerous impermeable units are evident by the absence of the microlog dark band response. With an average vertical permeability of zero (0), the middle confinement unit functions as an important secondary seal in the confinement system.

Upper Confinement Unit - This unit is composed of a 200' thick dense shale section with vertical permeabilities at or very near zero. The massive shales are clearly distinguishable on both logs. The upper confinement unit is immediately below the lowermost USDW in northwest Indiana and functions as a tertiary and final seal for the Mt. Simon injection zone.

The Great Lakes Region example of a confinement system has all the necessary features for preventing upward migration of injected fluids. The use of several wells logs in combination with fullhole core data provides a clear picture of how a confinement system functions as a cumulative sequence of geological barriers protecting all USDWs.

EXAMPLE OF GULF COAST REGION CONFINEMENT SYSTEM

The Gulf Coast Region includes the coastal portions of both Texas and Louisiana in which a majority of existing Class I wells are located. In contrast to the Great Lakes Region, the subsurface geology of the Gulf Coast Region is characterized by cyclic sand - shale sequences which form a great gulfward thickening wedge extending to depths well over 10,000'. These deposits consist of interfingering lenticular beds of fine to medium grained sands, shales and clays. The lenticularity of these beds prevents long range correlations and subdivision by electric log data. The lenticular nature of the Miocene sediments also makes them ideal candidates as disposal reservoirs. Massive high porosity and permeability deltaic sandstones are sandwiched inbetween massive wedges of low permeability shales which form the confinement system. On a regional basis, many of the deep sand units used for underground injection can be visualized as shaped as a "double convex lens", thickest at the middle and thinning out toward the edges.

A Class I well in southern Louisiana was selected as an example of a confinement system in the Gulf Coast Region and is illustrated in Figure 3. The example has a number of features which are common to Class I wells throughout the region. These include:

1. Multiple Injection Zones - Due to the relative abundance of thick high permeable sand units below the lowermost USDW, several sand bodies can be utilized by one or more injection wells. As can be seen from the small scale induction electric log, three injection zones are identified. The lower or deepest injection zone represents the completed interval of the Class I well from which the log was taken. The middle injection zone is used by a second nearby Class I well in order to segregate wastestreams and to minimize the pressure buildup in any single zone. The upper injection zone is used by a separate Class I well for the same reasons.

2. Thick Confinement Systems - Thick confinement systems characterize the Gulf Coast Region. This can be attributed to the availability of deep multiple injection zones and the rapid vertical transition of formation water quality from fresh to saline. The confinement system is so thick in the example that its entire length could not be feasibily illustrated in the detailed expanded lithologic section. Only the first several hundred feet of the confinement system above the lower and upper injection zones is discussed. However, the portions of the confinement system not expanded are virtually identical to the sections discussed.

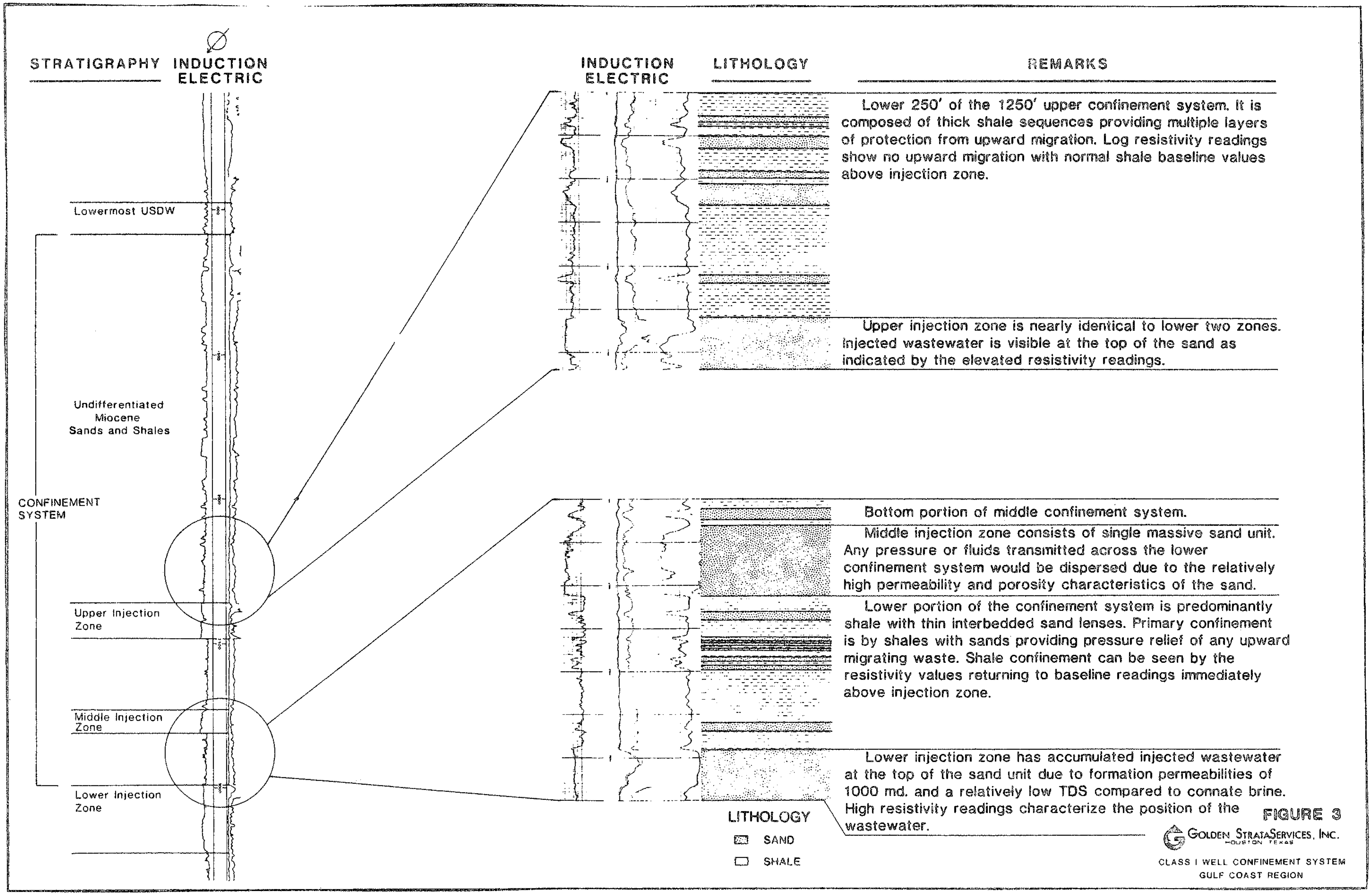


FIGURE 3

CLASS I WELL CONFINEMENT SYSTEM
GULF COAST REGION

3. <u>Confined Wastewater Shown on the Log</u> - One of the reasons that this Class I well was selected as the Gulf Coast Region example of a confinement system is that confined wastewater is actually represented on the log. This situation is rare because the wastewater must be in place prior to the drilling and subsequent logging of the well. The log has intersected two wastewater fronts which have been displaced radially from other existing Class I wells located a short distance away. Previously injected wastewater has accumulated in the top of the lower and upper injection zones and can be identified by a sharp increase in the resistivity curves.

The uppermost 40' of the lower injection zone has accumulated previously injected wastewater from a nearby Class I well. The wastewater because of its lighter density has segregated to the top of the sand unit on top of the denser formation brines. In addition, its relatively low TDS value can be seen by the elevated resistivity curves. In other words, a fresher liquid has a higher electrical resistance than a salt saturated brine. The lower injection zone is composed of a massive sand unit with permeability values often exceeding 1000 md. The high permeabilities have allowed the wastewater to move vertically within the sand body until it encounters a boundary, the confinement system shale.

The lower portion of the confinement system is immediately above the lower injection zone and extends to the base of the middle injection zone. Primary confinement is provided by the thick low permeability shales with the thin sand lenses providing pressure relief for any upward migrating wastewater. The log illustrates clearly that the shale provides confinement immediately above the lower injection zone. The transition from the sand in the injection zone to the shales of the confinement system, a sharp change in the log resistivities can be seen. The high resistivity rapidly returns to the normal baseline position as soon as the shale is encountered illustrating no evidence of wastewater and therefore excellent confinement.

The middle injection zone consists of a single massive sand unit utilized by adjacent Class I wells. Any pressure or fluids which might be transmitted across the lower confinement system would be dispersed within the middle injection zone due to the high porosity and permeability characteristics of the sand. However, no log indication of wastewater is shown for the middle injection zone.

The upper injection zone is nearly identical in most respects to the lower two injection zones. As in the lower injection zone, 14' of wastewater is indicated at the top of the unit by log resistivity values.

The lower 250' of the 1250' upper confinement system is composed of thick shale sequences providing numerous layers of protection from upward migration. The log resistivity values show no indication of additional upward migration. A normal shale baseline occurs immediately past the transition from sand within the injection zone and shale of the confinement system.

POTENTIAL FOR FLUID MOVEMENT THROUGH THE CONFINEMENT SYSTEM MATRIX

The potential for fluid movement through the confinement system matrix is a function of three parameters. These include:

1. The permeability of the individual lithologic units within the confinement system.
2. The induced pressure gradient resulting from the injection of fluids.
3. The thickness of the individual lithologic units.

Only after determining the specific lithology of the units of a confinement system such as the two previous examples, can an evaluation of the potential for upward migration be performed. Any discussion of monitoring a Class I well must center on the potential for fluid movement through the confinement system. The following discussion only examines flow through the rock matrix itself. Other mechanisms for circumventing the confinement system are covered separately in the next section.

Dr. Don L. Warner, one of the first people to evaluate confinement systems at Class I injection well sites, described matrix flow at the 1984 National Ground Water Quality Symposium.

> "If the confining layer is a clastic sedimentary rock such as the Eau Claire Formation, that is, it is composed of discrete sedimentary particles and is unfractured, then fluid flow will be through intergranular spaces. Shales and siltstones and gradations between them are examples of such rocks. Flow through the intercrystalline spaces in chemically deposited rocks such as limestones is also intergranular flow."

Although Warner uses the Eau Claire Formation as an example, it is just as applicable to the Gulf Coast Region which is also composed entirely of sedimentary rock sequences.

When viewed under a microscope, the individual grain particles of a lithologic unit system are seldom spherical. This is especially true of clay particles which are nearly flat. Rocks which are composed of predominately clay-rich sediments are called shales. Because they are deposited in water, the particles usually come to rest on their flat side, stacking on top of one another. Following deposition, deep burial and subsequent compaction, flow paths through the rock are significantly more tortuous in the vertical direction than in the horizontal. Consequently, as a rule, vertical permeability is always less than horizontal permeability. It is not unusual to find that vertical permeability is only 1/5 to 1/10 of horizontal permeability. This phenomenon is called "anisotropy" and is the rule rather than the exception. In confinement systems, anisotropy in conjunction with small particle size is the reason shales have naturally low vertical permeabilities. The shale lithology forms an effective seal of the injection zone.

A discussion of permeability and its relationship to the confinement system was also addressed by Don L. Warner at the 7th National Ground Water Quality Symposium in 1984 with relevant portions included below:

> "The permeability of rock is a measure of its capacity to transmit a fluid under an applied potential gradient. As with porosity, intergranular permeability is influenced by the grain properties of rocks that are composed of grains (sands, sandstones, siltstones, shales, etc.). However, whereas porosity is not theoretically dependent on grain size, permeability is strongly dependent on this property. The smaller the grains, the larger will be the surface area exposed to the flowing fluid. Since it is the frictional resistance of the surface area that lowers the flowrate, the smaller the grain size, the lower the permeability. Shales, which are formed from extremely small grains, have almost no permeability. This is why shales are selected as confining intervals. As with effective porosity, permeability also results from interconnected solution channels and fractures as well as from interconnected intergranular spaces."

> "Permeability values from core samples of units used for wastewater injection or petroleum production range from several darcys to less than one millidarcy, but an average value of less than 10 millidarcys for an overall interval would be considered to be very low, whereas a value of 100 - 1,000 millidarcys would be good to very good. Shales, which are considered to be suitable confining strata, have permeabilities in the order of 10^{-3} to 10^{-6} millidarcys, or thousands of times less than an adequate injection interval."

Low permeability shales make up a majority of the confinement systems illustrated in the two examples from the Great Lakes and Gulf Coast Regions. Although the relative permeability of a formation is best obtained through fullhole cores samples, these are not available for existing Class I wells where casings and cements prevent direct sampling. However, permeability information can also be obtained from adjacent wells, geophysical logs, pressure transient testing and nearby oil and gas production within a region.

In a multilayered confinement system such as the ones illustrated in Figures 2 and 3, any injected fluid that migrated vertically through a low permeability zone into a 1000 to 100,000 times more permeable zone would flow horizontally within the permeable zone toward areas of lower pressure. This effect is also related to the concept of anisotropy and grain size, which explains that horizontal permeabilities are 5 to 10 times greater than vertical permeabilities. Due to the depositional process of sedimentary units such as sandstones, the path-of-least resistance will be horizontal due to grain size and shape and deposition. This phenomena has a two-fold benefit to confinement. Migration through the impermeable layer(s) would tremendously reduce the vertical driving force of the injected fluid due to frictional losses and the more permeable layer(s) would radially disperse any fluids transmitted. In effect, vertical migration would be halted and fluid would be trapped in the first permeable unit. This mechanism was recently acknowledged by the Ohio Environmental Protection Agency (OEPA) in a document reprepared by an OEPA subcontractor during 1984. It stated that the:

> "Orders-of-magnitude differences between the permeabilities of the sandstone units and the confining shales units results in vertical flow in shale, and horizontal flow in sandstones, precluding upward vertical migration above the sandstone."

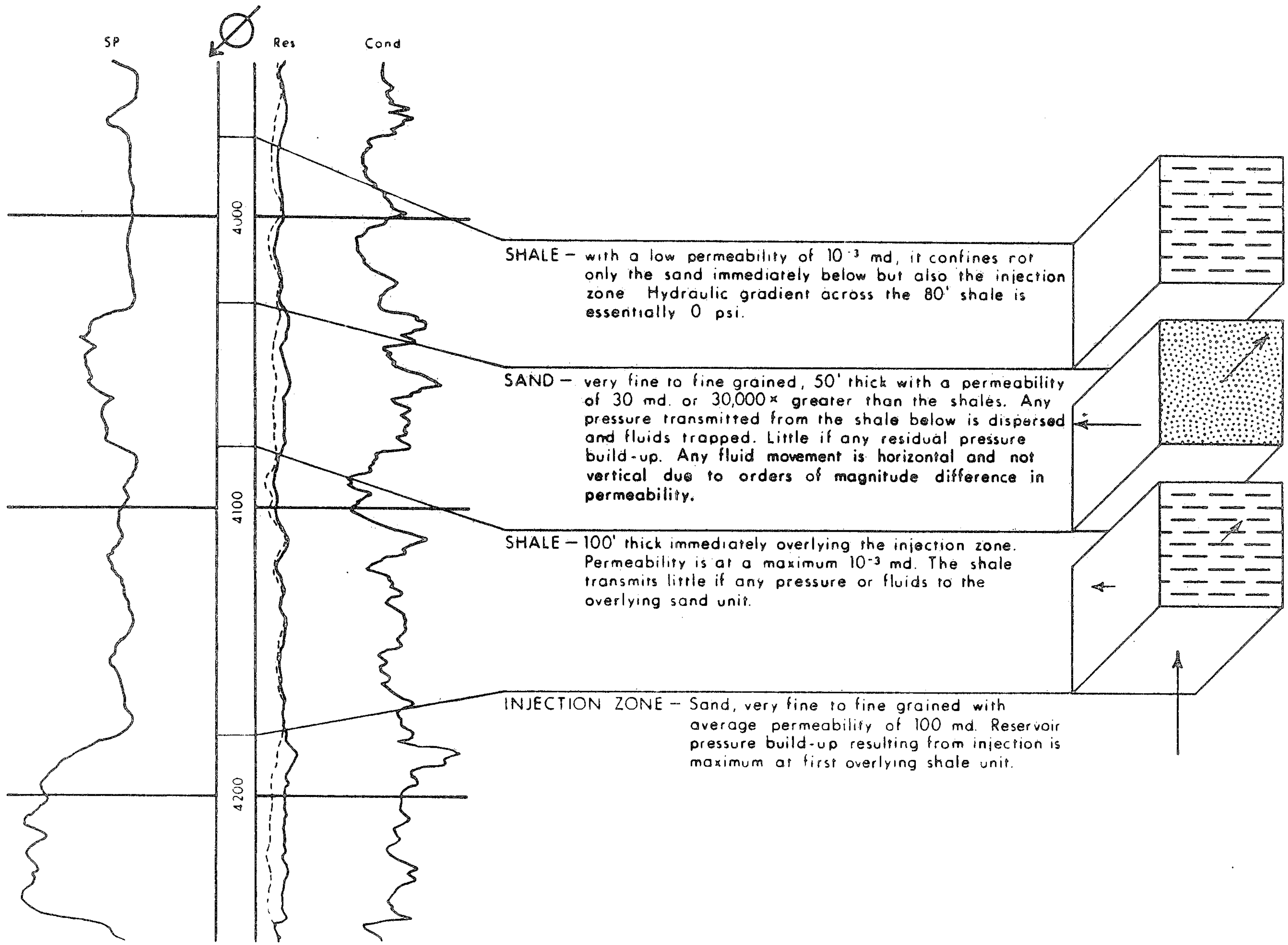
This concept is illustrated in Figure 4. The example is taken from a confinement system for a Class I well located within the Gulf Coast Region in South Texas. A portion of an induction electric log is used to show the lithologic units of the confinement system immediately overlying the injection zone. The top of the injection zone sands are at 4180' with an overlying shale and sand sequence. The injection zone is capped by 100' of dense shale followed by 50' shaley sand. Above this is another 80'± of shale. Although this type of sequence continues for several thousand feet, in this case the first 200' are used to provide a good example of how a confinement system functions.

A 100' thick shale unit immediately overlies the injection zone. Although fullhole core data is not available for the shale, a safe assumption is that the permeability would be less than 0.001 md. It can be demonstrated that the first shale unit is all that is needed to confine both fluids and pressure to the injection zone. Should any pressure or fluids be transmitted to the 50' thick sand unit above shale, the relatively high permeability of the sand would disperse the small residual pressure and effectively trap all upward migrated fluids. This type of confinement system is very similar to the previous examples and is excellent for preventing upward migration.

Using the above example, an estimate of the maximum theoretical rate of upward migration due to matrix flow across the first 100' shale unit can be calculated using a form of Darcy's law. The following equation has been previously utilized by an Ohio Environmental Protection Agency (OEPA), subcontractor in 1984, in an investigation of the potential for vertical migration at a commercial waste disposal well facility and is also referenced by Don L. Warner, 1984.

FIGURE 4

Effects of Multilayered Confinement System



$$q = \frac{k \Delta h}{\phi T} \quad \text{Equation No. 1}$$

Where: q = pore velocity (ft/day)

k = permeability (ft/day)

Δh = difference in hydraulic head across the Eau Claire (ft)

T = thickness of shale unit (ft)

ϕ = porosity

Data: $k = (.001 \text{ md}) \left(\frac{1 \text{ ft/day}}{0.3671 \text{ darcies}}\right) = 2.7 \times 10^{-6}$ ft/day

Δh = 1600' head (693 psi)

ϕ = 0.10

T = 100'

Solution: $$q = \frac{(2.7 \times 10^{-6} \text{ ft/day})\ (1600')}{(0.10)\ (100')}$$

q = .0004 ft/day

q = 0.16 ft/year

q = 1.6 ft/10 years

The calculated rate of upward migration through the matrix of the clastic sediments demonstrates the effectiveness of a confinement system. As can be seen, the calculated rate of fluid movement is insignificant. The useful life of an injection well is much shorter than the travel time even across the first confining bed.

The calculations used to evaluate confinement are very conservative in that the assumed pressure gradient of 1600' of head (693 psi) across the first shale is too high. The fluid pressure in an injection zone is greatest only at the immediate wellbore and declines logarithmically as the radial distance from the well is increased. The pressure will also vary with time, increasing as injection continues or declining if injection ceases or the flowrate is reduced. Pressure falloff has the effect of reducing the vertical pore velocity and increasing the level of head loss due to vertical migration.

These worst case models for upward migration through the matrix of the clastic sediments demonstrates the effectiveness of confinement systems present at the majority of existing Class I wells throughout the Great Lakes and Gulf Coast Regions.

CIRCUMVENTION OF CONFINEMENT

Potential migration mechanisms, other than matrix flow, which could result in the circumvention of the confinement system associated with a Class I well fall into two general categories. One category includes mechanical failure of well components such as tubing, packer and casing. The other takes into account other potential pathways through the confinement system such as improperly plugged wells, faulting, interconnected channels in the cement sheath surrounding the wellbore and hydraulic fracturing.

Each of these migration mechanisms is individually discussed as an introduction to the corresponding confinement monitoring techniques covered in the next section.

MECHANICAL FAILURE

Direct injection into an USDW can only occur through a mechanical failure of key well components. As can be seen from Figure 5, a hole in the long string casing would not result in direct injection of wastewater into formations other than the disposal reservoir unless failure of other mechanical components also occurs. This is because wastewater is isolated from contact with the casing by a sealed annulus. The annulus itself can be viewed as a long pressure vessel formed by the casing and tubing capped at the bottom by a packer and at the top by the wellhead.

Direct injection into formations other than the disposal zone through a casing leak can only happen in conjunction with a tubing and/or packer leak which would allow the wastewater to enter the annulus. The fact that failure of a single well component cannot cause direct injection into a USDW is a good example of the inherent safeguards designed into a Class I well. Direct injection into a USDW involves mechanical failure of a third key well component. For this to occur, the surface and long string casings must fail along with a tubing or packer leak which allows the wastewater to contact the casing. Table 1 is a list of the criteria necessary for direct injection to occur.

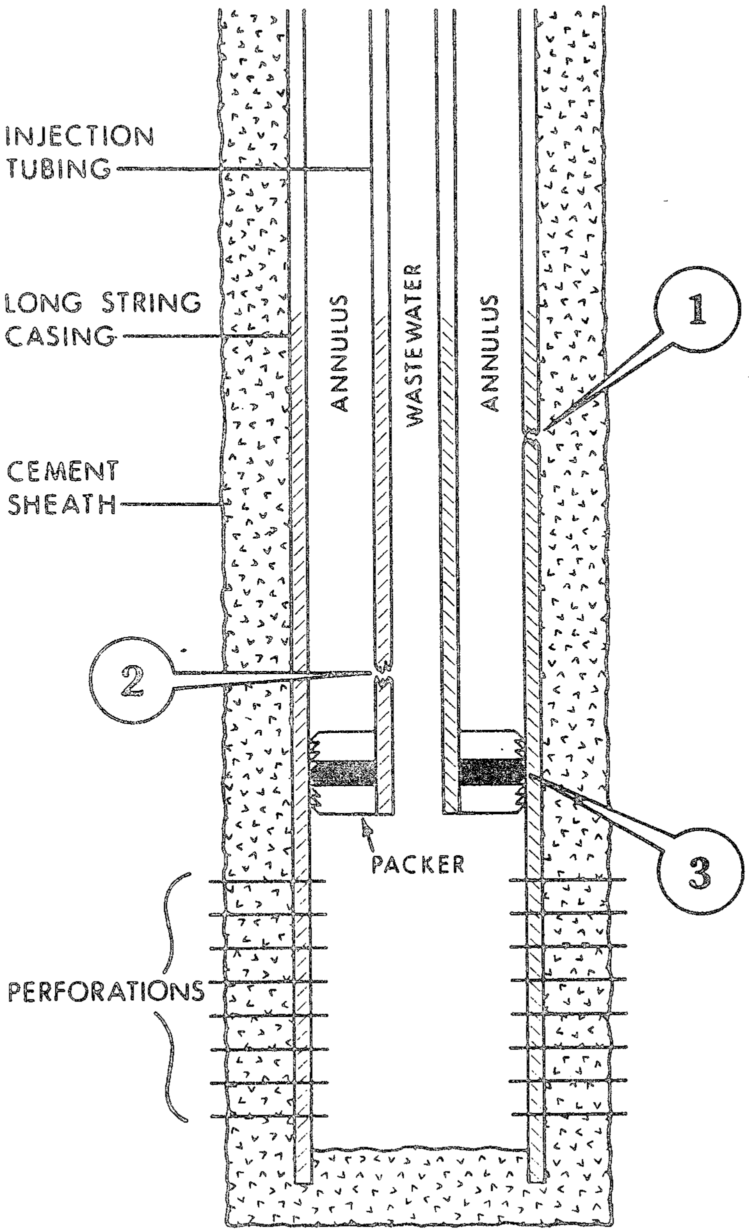
BREACH OF CONFINEMENT

A breach of confinement is defined as a hydraulic connection between the injection zone and a USDW aquifer above the confinement system. A breach of confinement can occur several ways in injection well systems as listed below and shown in Figure 6.

1. Unplugged Artificial Penetrations
2. Faulting or Other Complex Geologic Structures
3. Channel in Cement Adjacent to Wellbore
4. Hydraulically Fracturing the Confinement System

FIGURE 5

Potential Migration Mechanisms Resulting From Mechanical Failure



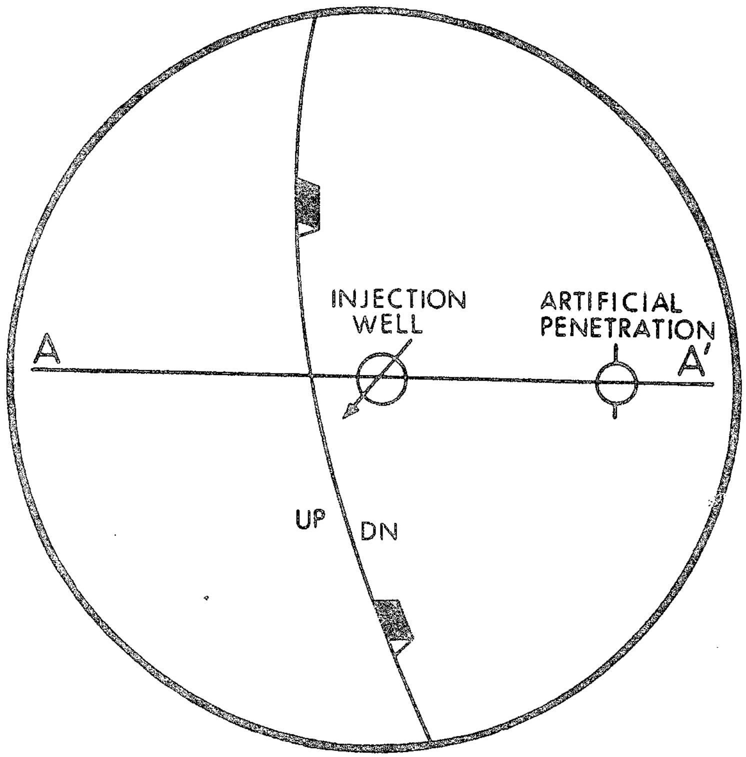
MIGRATION MECHANISM	SAFEGUARD
1. HOLE IN LONG STRING CASING	1a. DETECTED BY ANNULUS MONITORING SYSTEM 1b. CASING LEAK DOES NOT RESULT IN DIRECT INJECTION IT MUST OCCUR IN CONJUCTION WITH TUBING OR PACKER FAILURE WHICH ALLOWS WASTE INTO ANNULUS 1c. PERIODIC MECHANICAL INTEGRITY TESTING CHECKS CONDITION OF WELL COMPONENTS
2. HOLE IN TUBING	2a. DETECTED BY ANNULUS MONITORING SYSTEM 2b. LONG STRING CASING AND CEMENT CONFINE FLUIDS TO ANNULUS 2c. PERIODIC MECHANICAL INTEGRITY TESTING CHECKS CONDITION OF WELL COMPONENTS
3. PACKER LEAK	3. SAFEGUARDS IDENTICAL TO 2a,b,c

TABLE 1
CRITERIA FOR THE POTENTIAL OF DIRECT INJECTION

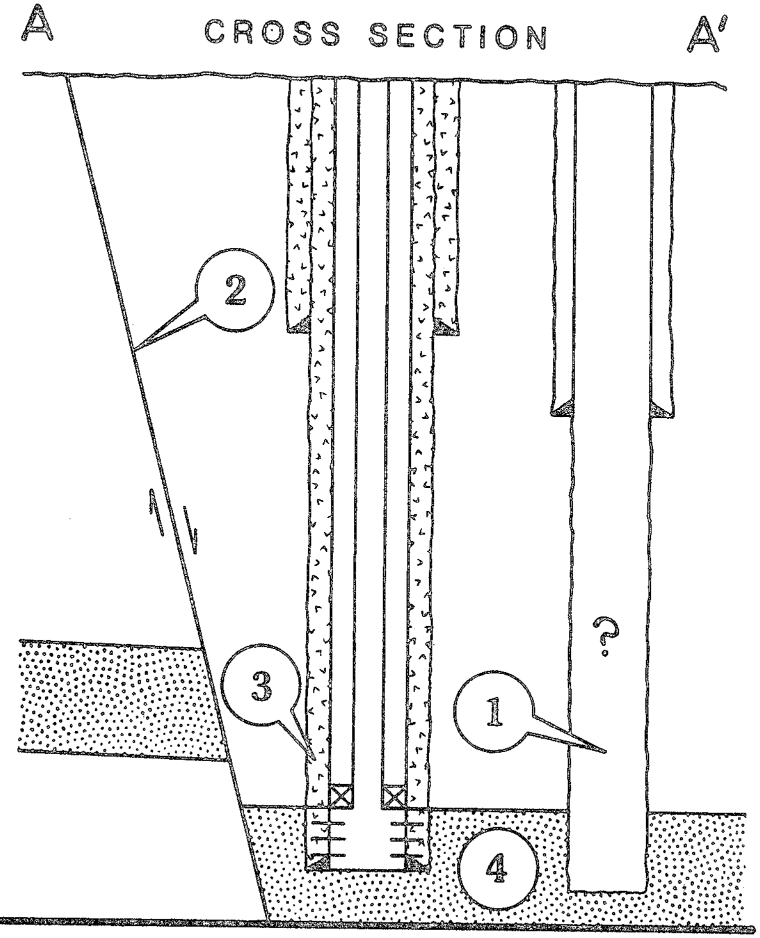
Mechanical Failure of Well Component	Results
long string casing only	no direct injection
injection tubing only	no direct injection
packer only	no direct injection
long string casing in conjunction with injection tubing or packer	potential for direct injection into formations above the injection zone
long string casing and surface casing in conjunction with injection tubing or packer	potential for direct injection into a USDW

Potential Breach of Confinement Mechanisms

FIGURE 6



MAP VIEW



POTENTIAL PATHWAY	SAFEGUARD
1. UNPLUGGED ARTIFICIAL PENETRATION	1 a. PROPERLY PLUG PROBLEM WELL b. LIMIT INJECTION OPERATIONS TO SAFE PRESSURE BUILDUP VALUES c. INSTALL MONITER WELL
2. FAULTING	2. SAME AS 1b AND 1c
3. CHANNEL IN CEMENT	3. CEMENT BOND LOGS AND MECHANICAL INTEGRITY TESTING
4. HYDRAULIC FRACTURING	4. REGULATE SURFACE INJECTION PRESSURES

Artificial Penetrations - An artificial penetration is defined to be any well within the area of review which penetrates or comes close to the top of the injection zone. Due to the relatively deep injection intervals associated with Class I wells, most artificial penetrations are a result of the exploration or production of oil and gas. As the most common source of subsurface geologic data needed to identify and evaluate an injection zone or confinement system, artificial penetrations pose a dilema.

In an area with very few or no artificial penetrations, the risk of interformational transfer of fluids through abandoned wellbores is virtually eliminated. This situation also means the lack of deep subsurface geologic information since the absence of wells and well log data are related. On the other hand, a larger number of artificial penetrations allows precise correlation of established log data due to the increased amount of information. However, the risk associated with discovering an unplugged well is higher due to the larger inventory of artificial penetrations. Within the Great Lakes Region, very few artificial penetrations are within the area of review of the Class I wells. In contrast, the Gulf Coast Region is well known for its extensive oil and gas production and large numbers of artificial penetrations. In most instances, a large majority if not all artificial penetrations are properly plugged and abandoned and do not threaten USDWs. Cement in combination with high density drilling fluids seal the wellbores of properly plugged wells and maintain the continuity of the confinement system. However, artificial penetrations that are unplugged, or those for which no plugging records are available, must be carefully investigated as a potential migration mechanism.

Faulting Or Complex Geologic Structures - Faulting or complex geologic structures are a potential migration mechanism only if they result in a breach of confinement. Faulting within the area of review surrounding a Class I well is very common throughout the entire Gulf Coast Region. In fact, it is responsible for much of the hydrocarbon production in Texas and Louisiana. The Great Lakes Region has a much lower incidence of subsurface faulting, none of which is close to any of the existing Class I wells.

There are basically three ways faulting can influence waste disposal operations. The first is that the disposal reservoir sands can be faulted against shales which act as a seal. For this to occur, the amount of vertical displacement of the fault must be greater than the thickness of the disposal reservoir so that the entire sand unit is sealed. The presence of this type of boundary may be seen as an increased rate of pressure build-up in the disposal zone during injection. If the vertical displacement of the fault is less than the thickness of the disposal reservoir, then the injection sands are just offset. In this case the sands are faulting against sands and flow can occur through the adjacent sands across the fault. A normal rate of pressure build-up is seen when this type of faulting occurs.

The second way faulting can influence an injection well is similar to the one discussed above; however, it deals with the confinement system. If the vertical displacement of the fault is greater than the thickness of the confining layers, it is possible to have flow around the confining layer. For this to happen, the disposal zone sands must be faulted against sands which form a "flow path" around the confining interval. Although this occurrence is a geologic possibility, it has a low probability since it requires the presence of very thick sands and thin interval of shale confining layers combined with a high displacement fault. This condition can be avoided by careful geologic analysis and the selection of a relatively deep injection zone with a sufficiently thick confinement system.

Faulting can influence a waste disposal operations in a third way. If the faulting acts as a conduit for vertical fluid migration, waste fluids may contaminate a USDW. Due to the very plastic nature of the Gulf Coast Region shales, faults tend to seal themselves allowing no vertical fluid movement up the fault plane. Evidence of this sealing tendency can be seen in the numerous oil and gas fields with a fault trapping mechanism. The large amount of hydrocarbon accumulation in these fields would not have occurred if faults served as a vertical conduit.

Numerous geological evaluations of the Great Lakes Region reveal few if any faults or complex geologic structures which might have an impact on existing disposal operations. The geological evaluations contained within the UIC permit applications and technical reports included the preparation of structural, contour and isopachous maps along with geologic cross sections illustrating the "undisturbed" layer cake stratigraphy.

<u>Channel In Cement Adjacent To Wellbore</u> - There is no question that the pressure build-up resulting from injection is greatest at the wellbore. This means that vertical migration is most likely to occur near the wellbore than at greater distances away. It is for this reason that Class I wells must be designed to provide a cement sheath seal to eliminate behind-the-casing migration. A pervasive channel in the cement adjacent to the wellbore may result in the potential of upward migration of wastewater into a USDW. Minimum lengths of bonded cement and casing required to provide a hydraulic seal have been established because of available cement logging techniques. For example, the predicted maximum cemented interval required for zone isolation behind a 7" casing is ten feet (10') (Schlumberger Cement Logging). This compares to the 3000' - 5000' of cement sheath surrounding the long string casing of most Class I wells.

<u>Hydraulically Fracturing The Confinement System</u> - Pressure build-up effects due to long term wastewater injection are an important factor in evaluating the potential for upward fluid movement into and above a confining system. As reservoir pressure increases, so do the upward driving forces against the confinement system barriers. This could

result in the hydraulic fracturing of the injection zone and eventually the confinement system, if not limited. However, for all Class I injection well systems, surface injection pressure (and thereby pressure build-up) are regulated by permit conditions to safe values under fracture pressure. Hydraulic fracturing of the injection zone or confinement system will not occur. It should also be noted that when injection ceases, formation pressure will dissipate over a relatively short period of time.

CONFINEMENT MONITORING TECHNIQUES

The HSWA and the pending reauthorization of the Safe Drinking Water Act (SDWA) have focused considerable public and regulatory attention on monitoring the confinement of a Class I well. To determine monitoring requirements, the first step is to recognize the importance of the geologic setting. The Great Lakes and Gulf Coast Regions are evaluated against the singlemost important criteria-adequacy of confinement.

MONITORING WELLS

The installation of monitoring wells is a common practice for monitoring other land disposal techniques and is proposed for Class I wells under the SDWA. However, the application of these techniques cannot be directly applied to Class I wells. In order to judge the need to install monitoring wells, the adequacy of confinement should be determined by an evaluation of the potential for fluid movement above a confinement system. If it can be demonstrated that no potential exists, an exemption from monitoring wells can be granted. The following evidence can be used to make this demonstration.

1. A sufficiently thick confinement system.
2. Absence of problem artificial penetrations.
3. Absence of faulting or complex geologic structures.

In short, a thick confinement system that is not breached by faulting or problem artificial penetrations does not require the installation of monitor wells.

Monitoring wells have historically not been used to detect upward migration through the matrix of the confinement system of Class I wells. Three factors are responsible for this.

1. Numerous geologic investigations support the conclusion that thick natural confinement systems prevent vertical migration. A common example includes the confinement required for hydrocarbon accumulation over geologic time. Another important illustration of confinement is the occurance of fresh groundwater overlying a saline aquifer.
2. Most existing Class I injection wells have thick confinement systems because injection typically occurs into deep subsurface formations providing large vertical separation from the lowermost USDW. It is for precisely this reason that underground injection is still commonly referred to as "deep well disposal".

Using the two examples of confinement systems, each is evaluated as to 1) a sufficiently thick confinement system followed by 2) problem artificial penetrations and 3) faulting and complex geologic structures.

A Sufficiently Thick Confinement System - Two examples where monitoring wells are not required due to the presence of a sufficiently thick confinement system are shown in Figures 2 and 3. These confinement systems range from 750' to 2000' thick and provide multiple layers of protection.

One unique feature of the Great Lakes Region confinement system is that it can be easily divided into two halves. The top half includes 400'+ of massive low permeability shale and carbonate and the bottom half is an alternating sequence low permeability shales and high permeability sands. Since there is no doubt that the upper half, with its measured low permeabilities, has sufficient thickness to prevent upward migration, let's focus the investigation on the lower half of the confinement system. If upward migration can be demonstrated not to occur in this lower portion, then the hundreds feet of additional low permeability shales above provide a substantial extra measure of confinement.

The upper Mt. Simon "B" cap shales (2540'- 2580') lie immediately above the lower Mt. Simon Sandstone injection zone and have a cumulative shale thickness of over 35', with individual beds of over 20'. If for example, a maximum pressure gradient of 700 psi is imposed across this 20' shale bed, the rate of upward migration can be calculated using Equation No. 1. Assuming a shale permeability of 10^{-3} md, the calculated rate of upward migration is .002'/day or .8'/year. Thus, the first shale unit could be considered to have sufficient thickness to confine wastewater for over 20 years. This is not a recommended thickness but this approach is a useful tool to demonstrate the adequacy of confinement.

Should any upward migration occur through the first shale unit, it would most probably not be wastewater but formation brines displaced from the injection zone and confining shales ahead of the injected wastewater. In any situation where there is upward migration, the displaced formation brine acts as a buffer retarding any actual wastewater migration.

Taking an even closer look at the example of the 20' shale unit, any fluid migrating upward would also be subjected to "salt filtration". This process is caused by the fine grained lithology of the shales, which act as semi-permeable membranes and was first recognized by Berry (1959). Salt filtration, as described below, may be an important process in sedimentary basins which are most often used for underground injection. As stated by Freeze and Cheery, 1979:

"When water and solutes are driven under the influence of hydraulic head gradients across semi-permeable membranes, the passage of ionic solutes through the membranes is restricted relative to water. The concentration of solutes on the input side of the membrane therefore increase relative to the concentrations in the output. This ion exclusion effect is referred to as salt filtering, ultrafiltration or hyderfiltration."

Shales cause salt filtering because the clay particles are squeezed so close together that the adsorbed layers of ions and associated water moleculës occupy much of the remaining pore space. Laboratory evidence (Freeze and Cherry, 1979) supports the conclusion that salt filtering is most likely to occur at depths below 1500' - 3000'. The overall result of salt filtration is to reduce the concentrations of the fluids driven through low permeability shales.

If it is assumed, for the purpose of illustration, that wastewater has traveled across the first 20' shale unit, the first permeable sand encountered would disperse any remaining residual driving force and migration would then be halted. The permeable sand units act as pressure relief valves in that they serve to disperse any residual pressure. Additionally, the pressure required to sustain upward migration cannot be maintained over short vertical distances. It is rapidly reduced due to the frictional loss experienced in traveling through extremely fine grained shales and pressure buildup falls off logarithmically, as the distance from the top of the injection zones increases.

The determination of sufficient confinement thickness must be judged against the pressure gradient imposed across the the confinement system. As a general rule, less confinement thickness is needed for lower induced pressure gradients. The Great Lakes Region is characterized by very low pressure build values which is due to the good reservoir characteristics of the Mt. Simon Sandstone. In fact, the increase in bottom hole pressure due to injection is way below 700 psi which was used in equation 1 to calculate the rate of upward migration. At one Class I facility in the Great Lakes Region the reservoir pressure in the Mt. Simon has only increased by 75 psi after the injection of over 600 million gallons of wastewater during a 13 year period. From a pressure gradient standpoint, the increase amounted to only to .02 psi/ft. The increases in pressure in the Mt. Simon will be temporary due to the enormous storage capacity relative to the small volume of injected wastewater. Additionally, following closure of a Class I well the bottom hole pressures gradually falloff to near original condition. In the long term, there is not sufficient hydraulic potential to cause vertical migration into USDWs.

An evaluation on the adequacy of confinement in the Great Lakes Region example concludes that a sufficiently thick confinement system is present and it can be demonstrated that there is no significant potential for fluid movement above the confinement system. Based upon adequacy of confinement, no monitoring wells are required and a waiver from the proposed SDWA regulations should be granted.

The same case can be made for the Gulf Coast Region example; however, the thickness of the confinement system is much greater in that the distance from the top of the injection zone to the lowermost USDW is several thousand feet. Figure 3 does provide a clear picture of the adequacy of confinement as detailed in the previous example in that in-situ wastewater can be seen on the log. The wastewater has a lower density than the connate water and thus has collected at the top of the injection zone and is responsible for changes in the log resistivity readings. The waste in this example has been effectively trapped by the first 20' to 40' shale layer immediately overlying the injection zone and no upward migration is noted.

These two examples are prototype cases for which the use of monitoring well to detect upward migration through the matrix of the confinement system are not required.

Artificial Penetrations - The absence of unplugged artificial penetrations is fundamental to the operation of a Class I well If an unplugged well penetrates through the confinement system, then the potential for upward migration exists at that point. It is significantly easier for a fluid to migrate up a previously drilled wellbore than through the matrix of the rock itself. The Great Lakes Region has one of the lowest concentrations of artificial penetrations within the area of review surrounding a Class I well. The Gulf Coast Region is best known as an active area for oil and gas exploration and production. It is not surprising that many artificial penetrations occur within this region.

A monitoring well is becoming an increasingly popular method to resolve the problem of unplugged artificial penetrations. Several have been installed in Texas and are proposed in other states. This monitoring method has several advantages over the more conventional technique of eliminating a problem artificial penetration - entering the old wellbore and properly plugging it. These include:

* Problem artificial penetrations usually have been installed in the 1920's and 1930's prior to the establishment of plugging requirements by the Oil and Gas regulatory agencies.
* Commonly very little information is available as to the subsurface completion and the condition of the downhole equipment left in the well. These unknowns greatly increase the risk associated with entering such a well. It may be impossible to access the remaining casing to place a cement plug.
* If the artificial penetration has an open wellbore, it is often impossible to know if it has been reentered precisely or if the formation has collapsed creating a bridge.
* If several artificial penetrations are contained within a small area, a single monitoring well can be installed in lieu of many. If pressure buildup is limited to prevent upward migration at the closest problem artificial penetration, then artificial penetrations at greater distances are also protected. This is because pressure buildup is reduced rapidly as the radial distance from injection is increased.

Should unplugged or problem artificial penetrations be discovered within the area of review of a Class I well facility, a monitor well may be an effective method to measure the reservoir pressure buildup. Figure 7 illustrates how a monitoring well can be used for this purpose.

In this figure, a monitoring well is sited between the problem artificial penetration and the Class I well. It is typically drilled through the injection zone with an identical completion as the Class I well. This allows the monitoring well to provide direct measurements of the reservoir pressure changes within the injection zone due to the operations of the injection well. The construction of such a monitor well in many ways reflects the design of the injection well itself. Multiple casings are cemented to the surface featuring waste compatible materials of construction.

From an operational standpoint, the injection activities are limited to a set bottom hole pressure in the monitoring well. If the bottom hole pressure in the monitor well reaches a certain predetermined level, then injection operations are halted. The monitoring well pressure limitations can be established by making reasonable assumptions regarding the hydrostatic overbalance of the drilling mud in the problem artificial penetration.

<u>Faulting and Complex Geologic Structures</u> - Faulting and complex geologic structures pose a similar risk to a confinement system as a problem artificial penetration. They both can result in a breach of confinement. Faulting and complex geologic structures have historically had only a minor effect on existing Class I wells. The reason for this is that few Class I wells have been sited close to faults or geologic structures that could pose a threat to USDWs. The siting of a Class I well is usually done following a thorough geologic feasibility study in which the effect of geologic structures are minimized.

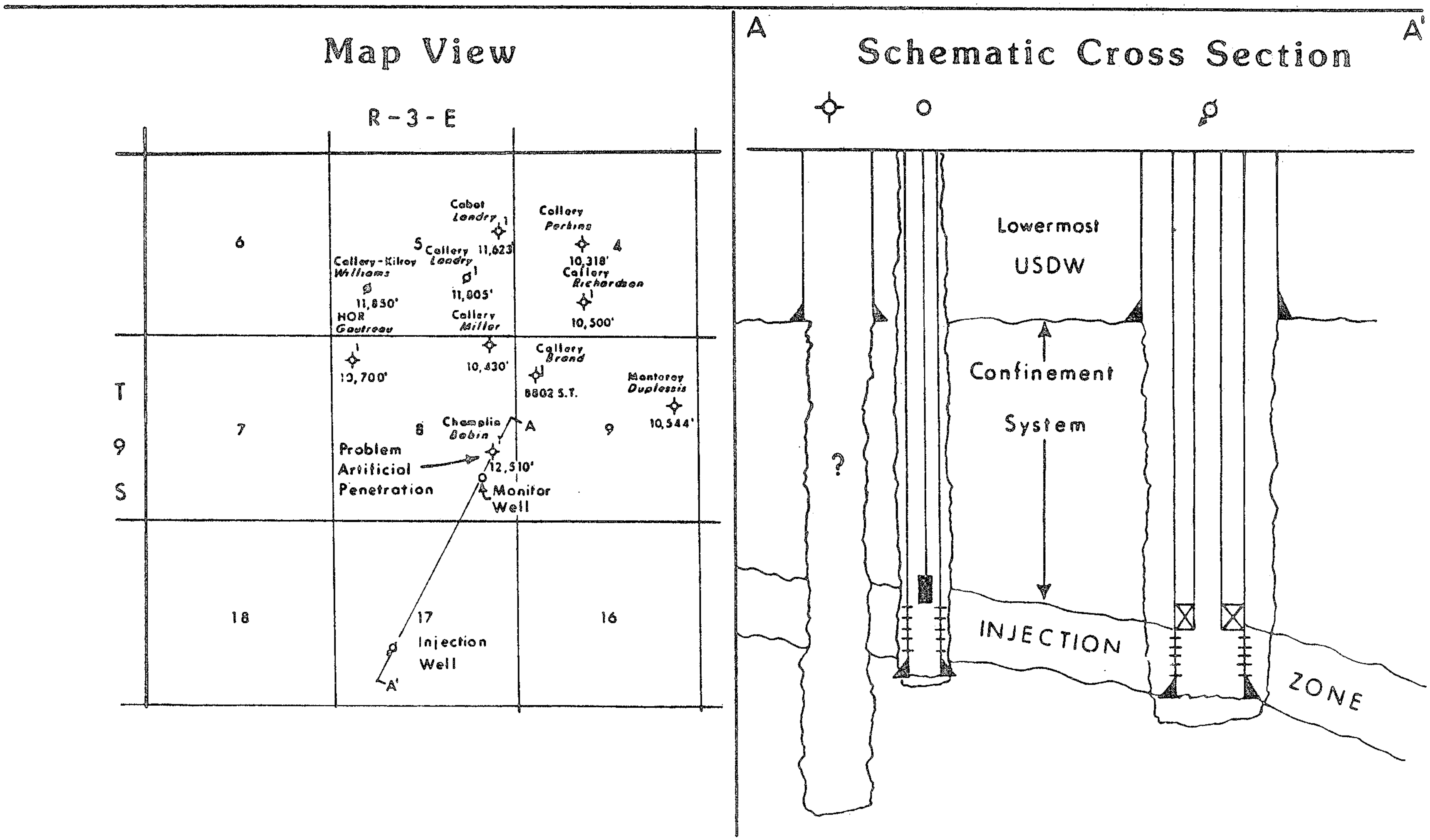
Throughout the Great Lakes Region no faulting is close enough to any of the existing Class I wells to pose a potential risk of upward migration. In contrast, the Gulf Coast Region has numerous subsurface faults which must be investigated on a site by site basis. A majority of the faults that do occur near a Gulf Coast Region Class I well have the following common properties which reduce or eliminate their effect on the injection operations. In these circumstances, no monitoring well is needed.

* The fault does not intersect the injection zone itself.
* The fault does not extend to the surface or to the lowermost USDW.
* The fault is sealing and does not compromise the confinement system.

Should a geologic investigation reveal that a fault poses a potential pathway for the contamination of a USDW, then a monitoring well could be considered. The siting and design of each well would have to conform to site specific conditions.

FIGURE 7

Monitoring Artificial Penetrations



WELL RELATED MONITORING SYSTEMS

Well related monitoring systems associated with a Class I well can be subdivided into three distinct systems. The first system monitors the internal well components for mechanical failure which might result in direct injection into formations other than the disposal reservoir. The second checks the near wellbore area for upward migration and the final one limits and records the surface injection pressure. The three well-related monitoring systems listed below are fundamental to providing the required high level of protection to USDWs.

1. Annulus Monitoring System - a simple yet highly effective method to provide first warning of even the smallest leak which could reduce well integrity.
2. Mechanical Integrity Testing - a series of geophysical logs and pressure tests to monitor the internal well components and external cement sheath.
3. Wellhead Instrumentation - standard instrumentation includes pressure gauges and continuous recorders designed to limit surface injection pressures to values below the amount need to cause hydraulic fracturing of the formation or confinement system.

Existing continuous annulus and wellhead systems combined with mechanical integrity testing have proven the best method to detect a breach in confinement due to well-related mechanical failure. An examination of each of these monitoring systems provides insight as the ability to monitor a Class I well whose mechanical components are thousands of feet underground and cannot be viewed directly.

<u>Annulus Monitoring System</u> - Class I wells monitor the integrity of the tubing, long string casing, packer and wellhead by built-in continuous monitoring system. The annulus can be described as a long cylindrical pressure vessel formed between the casing and tubing and sealed at the top by the wellhead and immediately above the injection zone by a packer. It remains fluid filled with a non-corrosive or inhibited fluid and is pressurized. A leak in any of the key well components is immediately indicated by a change in pressure. It should be emphasized that a single leak in any of the internal well components cannot lead to a direct injection into a USDW or formation other than the injection zone. In the event a leak is detected, the well can be immediately shut in, injection halted and the proper regulatory agency notified in compliance with the standard UIC permit conditions and limitations.

A typical pressurized annulus monitoring system is shown in Figure 8 and has a separate pressure chamber located at the surface adjacent to the wellhead. This arrangement has the following advantages:

* Annulus remains full of fluid through a range of operating pressures.
* Nitrogen pressure can be applied to the separate tank rather than directly to the wellhead.

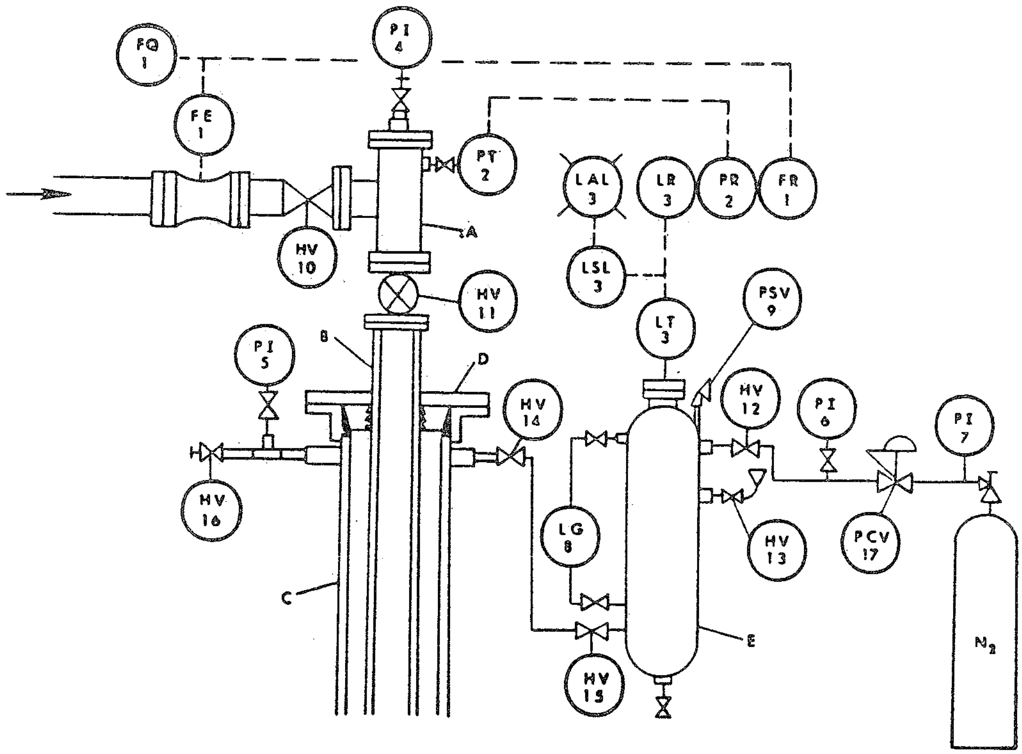


FIGURE 8

WELLHEAD AND ANNULUS MONITORING SCHEMATIC

A	Flow Tee
B	Tubing
C	Casing
D	Casing Head
E	Annulus Pressure Chamber
FE-1	Flow Sensing Element for Injected Fluid
FR-1	Flowrate Recorder
FQ-1	Flow Volume Totalizer for Injected Fluid
PT-2	Pressure Transmitter - wellhead tubing pressure
PR-2	Pressure Recorder - wellhead tubing pressure
LT-3	Level Transmitter - annulus pressure chamber level
LR-3	Level Recorder - annulus pressure chamber level
LSL-3	Low Level Switch - annulus pressure chamber level
LAL-3	Low Level Alarm - annulus pressure chamber level
PI-4	Pressure Gauge - wellhead tubing pressure
PI-5	Pressure Gauge - annulus pressure
PI-6	Pressure Gauge - annulus pressure chamber (during pressurized nitrogen)
PI-7	Pressure Gauge - nitrogen supply bottle
LG-8	Level Glass - annulus pressure chamber level
PSV-9	Pressure Relief Valve - annulus pressure chamber
HV-10	Wing Valve (supply valve) 2000 psi W.P.
HV-11	Master Valve 200 psi W.P.
HV-12	Nitrogen Supply Valve
HV-13	Annulus Pressure Chamber Fill Valve
HV-14	Annulus Pressure Valve (casing)
HV-15	Annulus Pressure Valve (pressure chamber)
HV-16	Annulus Fill/Bleed Valve
PCV-17	Nitrogen Pressure Control Valve

- Loss of well integrity can be visually observed by both pressure and fluid level changes.

Mechanical Integrity Testing - In Class I wells the area most likely for upward migration to occur is near the wellbore since the effect of pressure buildup is a maximum in this area. As in any well installation, the near wellbore area is the most sensitive area to be monitored. Class I wells are constructed to withstand the pressures and wastestreams injected and the area between the casing and wellbore is sealed with cement to eliminate the possibility for upward migration. Mechanical integrity testing is the method utilized to determine if a proper seal exists and periodically demonstrate that this area remains sealed.

As required under the UIC program, Part 40 CFR 146.08 (a.1 and a.2) all Class I wells must demonstrate mechanical integrity prior to final permit issuance and on a periodic schedule thereafter. Mechanical integrity testing can be compared to the standard automobile inspections that are required once a year. There purpose is the same as mechanical integrity testing in that a standard evaluation of key mechanical components is performed and repairs made if necessary. Mechanical integrity testing is designed to demonstrate that 1) there is no significant fluid movement through vertical channels adjacent to the injection wellbore and 2) there is no significant leak in the casing, tubing and packer annulus.

A variety of geophysical logging methods are utilized to demonstrate a Class I wells mechanical integrity during construction, workover or periodic testing. Table 2 is a listing of these methods and the role in monitoring that they perform.

A second part of mechanical integrity testing involves a short duration annulus pressure test. The annulus is pressurized to approximately 1.25 to 1.5 times the normal surface injection pressure. The EPA and many state UIC programs consider such a test successful if the annulus pressure decline is less than 3% to 5% of total pressure during the 30 minute to 1 hour duration of the test. This allows a representative testing of well components at pressures above what is normally experienced during normal injection operations.

A closer inspection of the annulus pressure test reveals how sensitive this method is to even the smallest leak. The following example calculates the volume of fluid equivalent from a leak of 15 psi (3% of a 500 psi test) over a 30 minute annulus pressure test. Assuming no expansion/contraction of the injection tubing and casing, the maximum allowed leak-off rate is calculated for a 4200 gallon (100 bbl) annulus.

(4200 gal.) (15 psi   p) $(3.5 \times 10^{-6}\ psi^{-1})$ = .0074 gpm

In other words, within 4000' to 5000' of casing and tubing, no more than 0.22 gal. can escape from all internal areas and still pass a demonstration of mechanical integrity.

TABLE 2
GEOPHYSICAL METHODS OF MONITORING

1. Cement bond logs and cement evaluation tool - Cement evaluation logs allow determination of casing of cement bond, formation to cement bond and hydraulic isolation of formations.
   - Identifies cement channels and quality of bonding.

2. Radioactive tracer surveys - These surveys utilize a gamma ray tool and an ejector pump that emits a small quantity of radioactive tracer fluid upon demand. The movement of tracer fluid is followed with the gamma ray tool, making possible, the detection of channels, casing, tubing and packer leaks.
   - Best log to evaluate upward migration through channels in the cement.

3. Temperature log - Temperature logs are used to measure changes in temperature to detect casing or tubing and fluid movement behind pipe.
   - Commonly used to find the top of cement during drilling operations.
   - Sometimes used to detect interformational transfer of fluids.
   - Specified by UIC regulations for MIT.

4. Noise log - The noise log detects naturally occurring sound energy caused by fluids or gases moving in or near the borehole and may be used to detect leaks.
   - Specified by UIC regulations to demonstrate MIT.

5. Flowmeter injectivity profiles - A flowmeter tools records numbers of revolutions per second of a turbine - like assembly (spinner) which is driven by movement of fluids past its blades.
   - Indicates amount of flow from an injection well into permeable zones in adjacent formations. This information is used to calculate effective reservoir thickness.
   - The effective reservoir thickness is an important parameter used to calculate radial movement.
   - The effective reservoir thickness can be compared to previous flowmeter profiles to determine the level of formation plugging prior to or following well stimulation.

A recent EPA opinion on mechanical integrity testing concluded that:

"The mechanical integrity tests, in states which have started to repermit wells, have uncovered a few shortcomings which could have potentially threatened USDWs. These shortcomings have been or will be corrected before any damage is done to USDWs. Thus the mechanical integrity testing requirement is proving to be an excellent tool in identifing a large number of mechanical defects and preventing contamination of USDWs (EPA, ODW, 1985)".

Wellhead Instrumentation - Wellhead instrumentation provides important monitoring of injection parameters and typically includes the following required equipment.

* Surface injection pressure gauge and continuous recorder to determine compliance with strict surface injection pressure limitation. By permit condition all Class I wells must maintain surface injection pressures at a level below the value needed to fracture the injection zone or confining system.
* Annulus pressure gauge and continuous recorder are required for the pressurized annulus system. The primary function of this intstrumentation is to provide the earliest warning of any loss in mechanical integrity.
* Flowrate and volume recorders continuously update the operator as to instantaneous and cumulative volumes injected into the well. This information is critical to project the position of the waste front throughout the life of the Class I well.

CONCLUSIONS

The HSWA and the reauthorization of the SDWA will affect the owners and operators of all Class I wells. Although it is still too soon to determine the exact implementation strategies of the EPA, an early picture is emerging.

In reference to the HWSA proposed ban on Class I wells, the primary options being considered by the EPA was recently addressed by Mike Cook, Director of the EPA, Office of Drinking Water. The plan calls for the EPA to establish a set of petition criteria to demonstrate the adequacy of confinement at each of the Class I well facilities. It would then be up to the owner/operator to 1) perform a well assessment and demonstrate that an individual well meets the criteria and 2) petition the EPA for an exemption from the proposed Class I well ban.

A similar approach is being taken by the SDWA concerning the installation of monitoring wells. As proposed by SDWA, monitoring will be required to detect the earlist possible migration of fluid into or in the direction of USDWs. However exemptions can be granted if it can be demonstrated that there is no potential for fluid movement above the confinement system. Nearly all the evidence indicates that a demonstration of confinement will be required by the EPA in a program designed to "tighten" regulatory constraints on Class I wells.

The assessment of Class I wells in the Great Lakes and Gulf Coast Regions was made to illustrate how a demonstration of confinement can be performed for the two principle geographic regions where Class I wells are sited. The first step in any such demonstration is to recognize the importance of the subsurface geologic environment.

The single confining layer concept often associated with Class I wells should be replaced with a more representative term - a confinement system. A confinement system includes all the stratigraphic units between the top of the injection zone and the lowermost USDW. It is multilayered, composed of both permeable and impermeable layers, functioning as a series of barriers to prevent vertical migration. In the Great Lakes Region the confinement system is predominately composed of the Eau Claire Formation and the upper portion of the Mt. Simon Sandstone. It is characterized by regionally continuous confining lithology providing multiple levels of confinement.

The Gulf Coast Region confinement system has cyclic shale and sand sequences with a lack of carbonate formations. This region is characterized by multiple injection zones, combined with confinement system that are thousands of feet thick.

A detailed description of the lithologic and reservoir characteristics of the confinement system is completed prior to estabishing the potential migration mechanisms. By identifying the pathways of fluid movement, an assessment of a Class I well site can then be performed by an evaluation of the adequacy of confinement. The following migration mechanisms were applied to the Great Lakes and Gulf Coast Regions and the following conclusions reached.

1. Migration Through the Confinement System Matrix - The potential for upward fluid movement was assessed by evaluating the vertical permeability, induced pressure gradient and the thickness of the lithologic units. The calculated rate of upward migration was insignificant when compared to the life of a typical injection well and the thickness of the confinement system. Additional calculations demonstrate that the pressure lost during vertical flow is many times greater than the maximum pressure buildup available.
2. Mechanical Failure - Mechanical failure of well components resulting in direct injection into formations other than the injection zone can only happen when two protection mechanisms fail. Direct injection through a casing leak must be in conjunction with a tubing and/or packer leak. Proven annulus monitoring systems offer reliable protection of USDWs from mechanical failure.
3. Breach of Confinement - Defined as a hydraulic connection between the injection zone and USDW, breach of confinement can occur several ways. These include unplugged artificial penetrations, faulting, cement channels and hydraulic fracturing. Both problem artificial penetrations and faulting must be evaluated on a case-by-case basis to determine the potential for upward migration. The Great Lakes Region has one of the lowest concentrations of artificial penetrations within an area of review, coupled with a lack of faulting or complex geologic structures. The Gulf Coast Region has a higher occurrence of both because of the structures and activities associated with the accumulation and subsequent production of hydrocarbons. Cement channels are detected and monitored by a variety of geophysical methods performed through periodic mechanical integrity testing. Hydraulically fracturing of the injection and confinement systems is controlled by the strict regulation of the surface injection pressures and flowrates.

An assessment on the adequacy of confinement for the Great Lakes and Gulf Coast Regions concluded that the installation of monitoring wells was not needed. This determination was based upon the evaluation of the potential for fluid movement above the confinement system. An exemption from these requirements can be granted, as established by the EPA, if there is a sufficiently thick confinement system, an absence of problem artificial penetrations and the absence of faulting or complex geologic structures. However, should a demonstration of confinement not be possible for a Class I facility due to a lack of one of the above three items, a monitoring well may be useful to assess the potential for upward migration. In these instances, it is most beneficial if the design and siting of the monitoring well match the site-specific geology and operation of the injection well.

Current monitoring required under the UIC regulations prevents migration into a USDW by several methods. These methods check the areas in which the potential for upward migration is the greatest; the internal well components and externally in the near-wellbore area. Internal well components are monitored for failure with a pressurized annulus system, periodic mechanical integrity testing and wellhead instrumentation. Near-wellbore migration is checked and monitored by geophysical logging methods associated with well installation and MIT.

In summary, this paper on confinement demonstrates that the EPA should make an affirmative determination that underground injection of hazardous waste should continue in areas where the geology can be demonstrated to provide adequate confinement. It thus is protective of human health and the environment because of its ability to contain injected wastewater over geologic time and isolate it from the accessible environment.

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LOVELACE, J.K., FONTENOT, J.W., AND FREDERICK, C.P., 2004
WITHDRAWALS AND WATER LEVELS, AND SPECIFIC
CONDUCTANCE IN THE CHICOT AQUIFER SYSTEM IN
SOUTHWESTERN LOUISIANA, 2000-03

science for a changing world

In cooperation with
Louisiana State University Agricultural Center
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Scientific Investigations Report 2004-5212

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Suggested citation:
Lovelace, J.K., Fontenot, J.W., and Frederick, C.P., 2004, Withdrawals, water levels, and specific conductance in the Chicot aquifer system in southwestern Louisiana, 2000-03: U.S. Geological Survey Scientific Investigations Report 2004-5212, 56 p.

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Conversion Factors, Datums, and Abbreviated Water-Quality Units

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	Flow rate	
foot per year (ft/yr)	0.3048	meter per year (m/yr)
million gallons per day (Mgal/d)	3,875	cubic meter per day (m^3/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 x °C) + 32

Vertical coordinate information in this report is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Horizontal coordinate information in this report is referenced to the North American Datum of 1927 (NAD 27).

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chloride in water are given in milligrams per liter (mg/L).

Withdrawals, Water Levels, and Specific Conductance in the Chicot Aquifer System in Southwestern Louisiana, 2000-03

By John K. Lovelace, Jared W. Fontenot, and C. Paul Frederick

Abstract

The Chicot aquifer system is the principal source of fresh ground-water supplies in southwestern Louisiana. Much of the area is rural and rice cultivation is the primary agricultural activity. About 540 million gallons per day were withdrawn from the aquifer system in southwestern Louisiana in 2000. Potentiometric-surface maps of the aquifer system were created for June 2002 and January 2003 to determine where water-level declines occur due to seasonal ground-water withdrawals. During June 2002, water levels in the aquifer system were more than 40 feet below the National Geodetic Vertical Datum of 1929 (NGVD 29) in parts of Acadia, Calcasieu, Evangeline, and Jefferson Davis Parishes, in an area that generally coincides with rice-farming areas. During January 2003, water levels were more than 30 feet below NGVD 29 in these areas.

From June 2002 to January 2003, water levels generally recovered between 5 and 20 feet in the Chicot aquifer system in most of Acadia and Jefferson Davis Parishes, southeastern Calcasieu Parish, and southern Evangeline Parish, in an area that generally coincides with rice-farming areas. These water-level changes are representative of the areal extent and magnitude of typical seasonal water-level fluctuations that occur in the aquifer system in response to seasonal ground-water withdrawals for rice irrigation.

The presence of saltwater has been documented in the Chicot aquifer system beneath coastal parishes and in some areas where the aquifer system merges with the stratigraphically adjacent Atchafalaya aquifer. Data collected during the period 1943 to 2003 from 1,355 wells screened in the massive, upper, and "200-foot" sands of the Chicot aquifer system and the Atchafalaya aquifer were used to delineate areas having similar specific conductance values and determine areas where wells are affected by saltwater. Near the outcrop area, specific conductance values in the Chicot aquifer system generally are less than 150 µS/cm (microsiemens per centimeter at 25 degrees Celsius). Specific conductance values increase south and east of the outcrop area. Specific conductance values generally range from 151 to 500 µS/cm in rice-farming areas of northwestern Acadia Parish, southeastern Allen Parish, western Evangeline Parish, and northern and central Jefferson Davis Parish. Specific conductance values generally range from 501 to 1,000 µS/cm in most of the remaining rice-farming areas. Specific conductance values often exceed 1,000 µS/cm in an area along the border between Calcasieu and Jefferson Davis Parishes near Iowa, Louisiana, parts of northeastern Cameron Parish, an area of northwestern and central St. Landry Parish; parts of Vermilion Parish, and several areas along the eastern boundary of the study area where the Chicot aquifer system merges with the Atchafalaya aquifer. The maximum specific conductance value, 12,100 µS/cm, is from a well in Cameron Parish.

During 2000-03, specific conductance was measured in 521 water samples from 166 wells screened in the Chicot aquifer system or the Atchafalaya aquifer. Specific conductance values exceeded 1,000 µS/cm in water samples from wells in Calcasieu, Cameron, Jefferson Davis, St. Landry, St. Martin, St. Mary, and Vermilion Parishes. Specific conductance values exceeded 2,000 µS/cm in only two wells—an irrigation well located about 2 miles south of Iowa and a USGS observation well used to monitor saltwater encroachment in east-central Vermilion Parish. Specific conductance values increased steadily at one well, from 1,090 µS/cm in April 2000 to 2,860 µS/cm in April 2003. Nearby wells did not show similar increases.

Specific conductance was measured hourly during pumping at two irrigation wells between 2000 and 2003. Specific conductance values were greater than 1,000 µS/cm in both wells, indicating the presence of saltwater near the wells. Specific conductance values generally fluctuated about 150 µS/cm at both wells, but no long-term trends in the specific conductance were evident in either well.

Introduction

The Chicot aquifer system underlies an area of about 9,000 mi^2 in southwestern Louisiana (fig. 1) and is the principal source of fresh ground-water supplies in the region. Much of the area is rural, and rice cultivation is the primary agricultural activity. Withdrawals from the aquifer system, primarily for

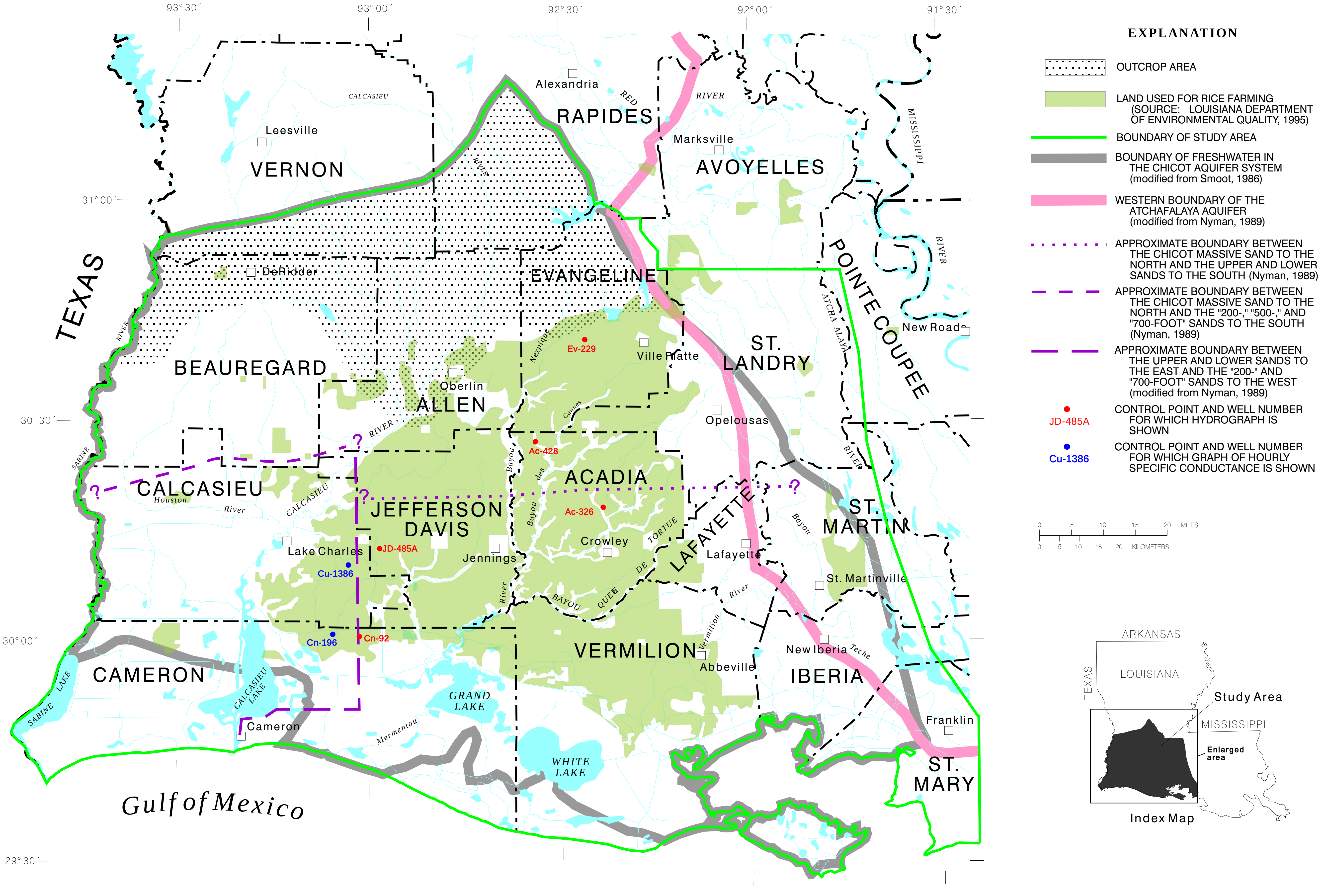


Figure 1. Location of the study area in southwestern Louisiana.

rice irrigation, have caused water levels to decline as much as 100 ft beneath some rice-farming areas of southwestern Louisiana since the early 1900's, creating an elongated cone of depression in the water-level surface over much of the region (Zack, 1971, p. 7-9 and pl. 2). In 1999, about 610,000 acres of rice were planted in southwestern Louisiana (fig. 1) (Louisiana Cooperative Extension Service, 2000). The water withdrawal rate from the aquifer system for rice irrigation in 2000, which was estimated based on 1999 acreage, was about 540 Mgal/d (Sargent, 2002, p. 17 and 92). Figure 2 shows water withdrawal rates for rice irrigation in southwestern Louisiana from 1960 to 2000.

From 1990 to 2000, water levels at several observation wells screened in the Chicot aquifer system and located in rice-farming areas declined at an average rate of 1 to 2 ft/yr (Tomaszewski and others, 2002, p. 11). Water levels in some areas of the aquifer system also fluctuate seasonally, primarily in response to ground-water withdrawals for rice irrigation (Nyman and others, 1990, p. 17), and wells in these areas could be affected seasonally.

The presence of saltwater[1] has been documented in the Chicot aquifer system beneath coastal parishes, in some areas where the aquifer system merges with the stratigraphically adjacent Atchafalaya aquifer, and in isolated bodies of saltwater near Lake Charles, Iowa, and south of Abbeville, Louisiana (Nyman, 1984). Seasonal pumping for rice irrigation has altered flow directions in the Chicot aquifer system and can induce lateral or upward movement of saltwater (Nyman, 1984, p. 1). Some irrigation wells screened in the aquifer system may be affected by saltwater encroachment, especially during periods of increased pumping in response to drought conditions.

Some farmers and residents of southwestern Louisiana are concerned that water levels in the Chicot aquifer system may decline below pump intakes in their wells, leaving them without water, or that their wells will be affected by saltwater encroachment. Current (2000-03) information is needed to (1) determine the location, duration, and magnitude of seasonal water-level declines; (2) delineate areas where wells are affected by saltwater; and (3) determine whether specific conductance, an indicator of saltwater, is increasing in water from wells in these areas. In response to this need, the U.S. Geological Survey (USGS), in cooperation with the Louisiana State University Agricultural Center, Louisiana Cooperative Extensive Service (LCES), and the Louisiana Rice Research Board, established a study in 2000 to monitor water levels and specific conductance in wells screened in the Chicot aquifer system over a 3-year period. Results of this study were reported periodically; potentiometric-surface maps and data for June 2000 and January 2001 were published in Lovelace and others (2001; 2002). This is the third and final report.

Purpose and Scope

This report describes water withdrawals, water levels, and specific conductance in the Chicot aquifer system in southwestern Louisiana during 2000-03. Trends in water levels and specific conductance also are discussed. Maps illustrate the potentiometric surface of the massive, upper, and "200-foot" sands of the aquifer system during June 2002 and January 2003. Water-level data from 141 wells used to construct the potentiometric surfaces are presented in a table. A map, based on data collected during 1943-2003, shows areas having similar specific conductance values in the massive, upper, and "200-foot" sands of the aquifer system. Specific conductance data collected during 2000-03 from 166 wells in southwestern Louisiana, are presented in a table. Graphs of water level and specific conductance data from selected wells also are presented. All data presented are on file at the USGS office in Baton Rouge, Louisiana, and stored in the USGS National Water Information System data base.

Data presented in this report establish baseline conditions that could enable current (2003) and future farmers, agricultural agents, and water-resources managers to determine the effects of ground-water withdrawals on water levels and water quality in the Chicot aquifer system. Results of this study may help improve understanding of conditions in similar coastal settings in other areas of the United States.

Description of Study Area

The study area includes all or parts of 15 parishes in southwestern Louisiana: Acadia, Allen, Beauregard, Calcasieu, Cameron, Evangeline, Lafayette, Iberia, Jefferson Davis, Rapides, St. Landry, St. Martin, St. Mary, Vermilion, and Vernon Parishes (fig. 1). The climate is generally warm, humid, and temperate. The average annual temperature is about 20^{o}C and the average annual precipitation is 55 in. (National Oceanic and Atmospheric Administration, 1995, p. 7, 9).

Data Collection and Methods

Water levels were measured using steel or electrical tapes marked with 0.01-ft gradations. Wells in which water levels were measured were not being pumped at the time the measurements were made. In addition, water levels were measured hourly at five wells located in rice-farming areas during 2000-03 using pressure transducers and data recorders.

Water samples for analysis of specific conductance and chloride concentration were collected from wells at a spigot or other discharge outlet. Many of the water samples were col-

[1]For the purposes of this report, saltwater is defined as water containing greater than 250 mg/L of chloride. Concentrations of chloride greater than 250 mg/L exceed the Secondary Maximum Contaminant Level (SMCL) for drinking water (U.S. Environmental Protection Agency, 1992). SMCL's are established for contaminants that can adversely affect the aesthetic quality of drinking water. At high concentrations or values, health implications as well as aesthetic degradation also may exist. SMCL's are not federally enforceable, but are intended as guidelines for the states.

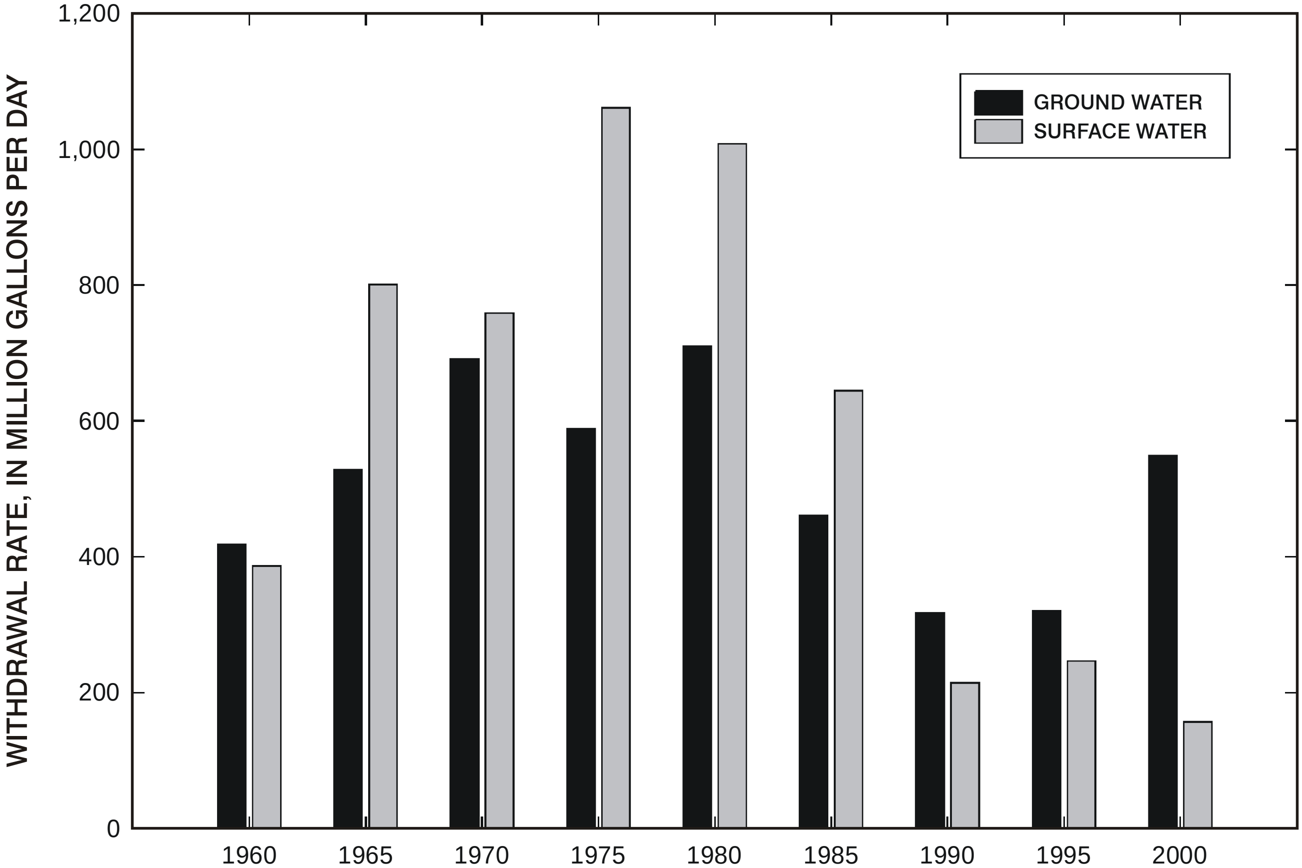


Figure 2. Water withdrawal rates for rice irrigation in southwestern Louisiana, 1960-2000 (Snider and Forbes, 1961; Bieber and Forbes, 1966; Dial, 1970; Cardwell and Walter, 1979; Walter, 1982; Lurry, 1987; Lovelace, 1991; Lovelace and Johnson, 1996; Sargent, 2002).

lected by well owners, farmers, or LCES agents; bottles and instructions on how to sample were supplied by the USGS. These samples were sent to the USGS office in Baton Rouge where they were analyzed for specific conductance using a hand-held or bench-top conductivity meter. To accurately identify and verify locations of wells sampled by well owners, farmers, or LCES agents, all wells were visited and many were resampled by USGS personnel. To increase the areal coverage of sampled wells, additional wells in the study area were sampled by USGS personnel. Samples collected by USGS personnel were analyzed for specific conductance using a hand-held meter in the field. Sample collection and measurements of specific conductance made in the field or at the USGS office in Baton Rouge were in accordance with methods described in U.S. Geological Survey (1997-present). Samples collected by USGS personnel for analysis of chloride concentrations were sent to a USGS laboratory in Ocala, Florida, where they were analyzed for dissolved chloride and specific conductance using laboratory methods described in Fishman and Friedman (1989).

Specific conductance and temperature were measured hourly during 2000-03 at two irrigation wells using a conductance meter and data recorder. The probe to the conductance meter was placed in a custom-made receptacle through which water flowed while the well pump was running. When the pump stopped, the receptacle drained. The periods during which the pump was not running were evident from temperature fluctuations, and data collected during these periods were discarded. Temperature data are not presented in this report.

State well-registration records currently (2003) list about 3,200 active irrigation wells that are screened in the Chicot aquifer system. Less than 100 of these wells are screened in the deeper sands, which include the lower sand and the “500-foot” and “700-foot” sands of the Lake Charles area (Z. “Bo” Bolourchi, Louisiana Department of Transportation and Development, written commun., 2003). Therefore, for the purposes of this report, references to the Chicot aquifer system in following sections refer to the Chicot massive sand, upper sand, and “200-foot” sand of the Lake Charles area unless otherwise indicated.

Previous Investigations

Since the early 1900's, many studies have focused on the occurrence and use of ground water, declining water levels, and saltwater encroachment in the Chicot aquifer system in southwestern Louisiana. Harris (1904) presented information about the underground waters of southwestern Louisiana and included a section on their use for water supplies and rice irrigation. Stanley and Maher (1944) reported on declining water levels in Acadia and Jefferson Davis Parishes due to ground-water withdrawals for rice irrigation. Jones (1950a) discussed water quality and the occurrence of saltwater in the Chicot aquifer system and presented a map showing the maximum depth of occurrence of fresh ground water throughout southwestern Louisiana. Jones and others (1954) presented the first comprehensive report on the geology and ground-water resources of southwestern Louisiana, presented maps of the Chicot aquifer system and the base of freshwater, and discussed the presence of saltwater and possibilities of saltwater encroachment in basal sands and coastal areas of the aquifer system. Harder (1960) presented a detailed report on the geology and ground-water resources of Calcasieu Parish, including a discussion of the occurrence and mobility of saltwater in the "200-foot" sand.

Fader (1957) updated the base-of-freshwater map by Jones and others (1954) and suggested five possible reasons for the presence of saltwater in the Chicot aquifer system: (1) incomplete flushing of the aquifer by freshwater, (2) lateral movement through formations, (3) downward seepage from surface sources, (4) vertical movement through underlying or overlying materials, and (5) upward movement along faults or around salt domes. Whitman and Kilburn (1963) discussed the occurrence and inland movement of saltwater in coastal areas of the upper sand due to increased ground-water withdrawals. Harder and others (1967) presented maps of the freshwater-saltwater interface in the upper sand and discussed the rate of encroachment.

Zack (1971) summarized the results of 10 years of monitoring chloride concentrations in water from 30 wells of a network established to monitor saltwater intrusion in the Chicot aquifer system. Nyman (1984) summarized chloride and specific conductance data collected by the USGS from wells in the Chicot aquifer system since 1937, focusing on data from the network. Nyman (1989) presented maps showing the range of various water-quality constituents and properties, including specific conductance, in the Chicot aquifer system. Lovelace (1999) updated the study by Nyman (1984) with chloride data collected during 1995-96. Potentiometric-surface maps of water levels in the Chicot aquifer system were published in many of these reports. Most recently, Tomaszewski and others (2002) determined trends in ground-water levels in monitor wells screened in the Chicot aquifer system for the approximate period 1990-2000.

Acknowledgments

The authors gratefully acknowledge the assistance of rice farmers who collected water samples from their wells and sent them to the USGS for analysis. The authors also gratefully acknowledge the assistance and cooperation of public-water suppliers and private well owners who allowed water levels to be measured in their wells. The authors especially want to thank Eddie Eskew, Keith Fontenot, Howard Cormier, Ron Levy, Jerry Whatley, and Gary Wicke, County Agents of the Louisiana Cooperative Extension Service, who initiated contacts with many of the land owners and farmers, assisted in sample collection, and were instrumental in developing the study. Thanks also to Z. "Bo" Bolourchi, Chief, Public Works and Water Resources Division, Louisiana Department of Transportation and Development, for providing well information that was used during this study.

Hydrogeology

The Chicot aquifer system underlies most of southwestern Louisiana and parts of eastern Texas. The system is composed of deposits of silt, sand, and gravel separated by units of clay and sandy clay. The system dips and thickens toward the south and southeast. The sand units grade southward from coarse sand and gravel to finer sediments and become increasingly subdivided by clay units. Eastward, toward the Atchafalaya River area, the Chicot aquifer system is overlain by and hydraulically connected to the Atchafalaya aquifer (Nyman, 1984, p. 4).

The Chicot aquifer system has been divided into three subregions in Louisiana based on the occurrence of major clay units. In the northern part of the study area, which includes the outcrop area, the aquifer system is undifferentiated, mainly consisting of a single massive sand. The approximate southern boundary of the massive sand is shown in figure 1. South of the massive sand, from eastern parts of Calcasieu and Cameron Parishes to the Atchafalaya River, the Chicot aquifer system includes an upper and lower sand unit (Whitman and Kilburn, 1963, p. 10). In most of Calcasieu Parish and central and western Cameron Parish, the aquifer system is subdivided into the "200-," "500-," and "700-foot" sands, named after their depths of occurrence in the Lake Charles area (Jones, 1950b, p. 2). The "200-foot" sand is stratigraphically equivalent to, and continuous with, the upper sand. Figure 3 shows a partial hydrogeologic column of aquifers and aquifer systems in southwestern Louisiana.

Recharge to the Chicot aquifer system is from infiltration of rainfall, vertical leakage, and lateral flow. Recharge from rainfall occurs in areas where the system crops out in northern Allen, Beauregard, and Evangeline Parishes and in southern

System	Series	Aquifer system	Aquifer		
			Outcrop area	Lake Charles area	East of Lake Charles
Quaternary	Pleistocene	Chicot aquifer system	Chicot aquifer, undifferentiated (massive sand)	“200-foot” sand of Lake Charles area	Chicot aquifer, upper sand unit
				“500-foot” sand of Lake Charles area “700-foot” sand of Lake Charles area	Chicot aquifer, lower sand unit

Figure 3. Partial hydrogeologic column of aquifers in southwestern Louisiana (modified from Lovelace and Lovelace, 1995, p. 10).

Rapides and Vernon Parishes (fig. 1). In these areas, precipitation infiltrates sandy soil and moves slowly downdip toward points of discharge. Recharge from vertical leakage occurs through overlying and underlying confining units. Recharge by lateral movement of water occurs from the Atchafalaya aquifer (Nyman and others, 1990, p. 14). A computer simulation of the aquifer system indicated that, under 1981 conditions, more than 90 percent of the water entering the Chicot aquifer system was discharged as pumpage, and 65 percent of the water pumped from the rice-farming area was supplied by recharge from the surface (Nyman and others, 1990, p. 33).

Withdrawals and Water Levels

During most of 1999 and 2000, southwestern Louisiana experienced below-average precipitation compared to the 30-year period 1971-2000 (fig. 4) and moderate to severe drought conditions (Louisiana Office of State Climatology, 1999-2003). Consequently, ground-water withdrawals for rice irrigation increased substantially during this period (fig. 2) (Sargent, 2002, p. 127). In addition, many coastal streams and canals normally used for irrigation supplies were inundated by saltwater from the Gulf of Mexico because of the lack of freshwater flushing that normally occurs after precipitation (Louisiana State University Agricultural Center, 2000). A comparison of data in water-use reports for 1990, 1995, and 2000, indicates that surface-water withdrawal rates for rice irrigation decreased and ground-water withdrawal rates for rice irrigation increased in Cameron and Vermilion Parishes in 2000 (Lovelace, 1991; Lovelace and Johnson, 1996; Sargent, 2002), presumably to offset the loss of surface-water supplies.

The total water requirement for rice cultivation during the growing season, which typically extends from February through June, is between 36 and 42 in. During an average year, about half of this water is supplied by precipitation and half is supplied by irrigation (Covay and others, 1992). Zack (1971) showed that the amount of ground water withdrawn in southwestern Louisiana in any particular year is inversely proportional to the total precipitation during the rice-growing season. Seasonal water withdrawals for rice irrigation typically begin in February and end in June. Consequently, water levels in the Chicot aquifer system typically decline from February through June in the rice-farming areas and potentiometric-surface maps for June generally show the lowest annual water levels (Lovelace and others, 2002). After June, water levels typically begin to recover (rise) and potentiometric-surface maps for January generally show the highest annual water levels (Lovelace and others, 2001).

To determine the magnitude and areal extent of water-level declines caused by seasonal ground-water withdrawals for rice irrigation, water-level data from 141 wells screened in the massive, upper, and “200-foot” sands (table 1) were collected. These data were used to construct potentiometric-surface maps of the Chicot aquifer system for June 2002 and January 2003.

During June 2002, the highest water level measured in the Chicot aquifer system, more than 160 ft above NGVD 29, was measured in the outcrop area in northern Beauregard Parish (fig. 5). Water levels were more than 40 ft below NGVD 29 in parts of Acadia, Calcasieu, Evangeline, Jefferson Davis, and adjacent parishes, in an area that generally coincides with rice-farming areas. The lowest water level, 80 ft below NGVD 29, was measured at well Ev-751 in southern Evangeline Parish. A comparison of the shapes and locations of the -50-ft, -60-ft, and -70-ft contours on the potentiometric-surface maps for June 2000 (Lovelace and others, 2001, fig. 3) and June 2002 (fig. 5) indicates that water levels in the Chicot aquifer system responded similarly to water withdrawals for rice irrigation during the 2000 and 2002 rice-growing seasons.

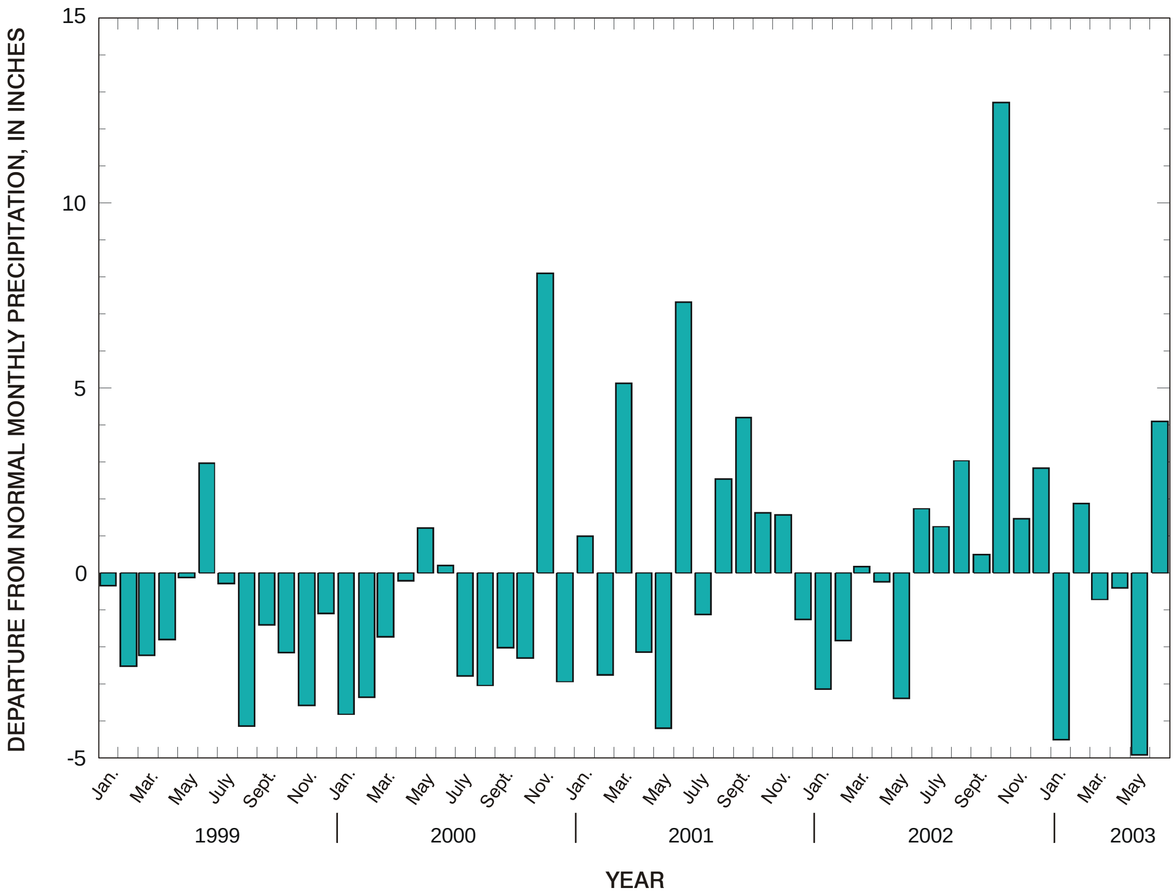


Figure 4. Departure from normal monthly precipitation (1971-2000) in southwestern Louisiana, January 1999 through June 2003 (Louisiana Office of State Climatology, 1999-2003).

During January 2003, the highest water levels, more than 160 ft above NGVD 29, were measured in the outcrop area of the Chicot aquifer system in northern Beauregard Parish (fig. 6). Water levels were more than 30 ft below NGVD 29 in parts of Acadia, Calcasieu, Evangeline, Jefferson Davis, and adjacent parishes, in an area that generally coincides with rice-farming areas (fig. 6). The lowest water levels, more than 60 ft below NGVD 29, were measured in wells Ac-929 in northern Acadia Parish and Ev-79 in southern Evangeline Parish. The similarities between the shapes and locations of the -40-ft and -50-ft contours on the potentiometric-surface maps for January 2001 (Lovelace and others, 2002, fig. 1) and January 2003 (fig. 6) indicate that water levels in the Chicot aquifer system recovered to similar levels after the 2000 and 2002 rice-growing seasons.

From June 2002 to January 2003, water levels recovered throughout most of the Chicot aquifer system in the study area in response to reduced withdrawals after the rice-growing season (fig. 7). Throughout much of the aquifer system, water levels recovered less than 5 ft. However, in most of Acadia and Jefferson Davis Parishes, southern Evangeline Parish, and southeastern Calcasieu Parish, in an area that generally coincides with rice-farming areas, water levels generally recovered between 5 and 20 ft. The magnitude of the water-level increase and the shape of the area over which water levels recovered more than 5 ft are generally consistent with the water-level recovery that occurred between June 2000 and January 2001 (Lovelace and others, 2002, fig. 4). The water-level changes shown in figure 7 and the previous water-level-change map are typical of the magnitude and areal extent of seasonal water-level fluctuations that occur in the Chicot aquifer system in response to seasonal ground-water withdrawals for rice irrigation.

To determine the duration of seasonal water-level declines due to ground-water withdrawals for rice irrigation, water levels in the Chicot aquifer system were measured hourly at five wells in the rice-farming areas during 2000-03 (fig. 8). The water levels at these wells typically declined between 10 and 25 ft, beginning in February or March and continuing through May or June. After June, water levels began to recover and generally continued to rise until seasonal ground-water withdrawals began the following year. Slight water-level declines, which often occurred during October, probably were due to withdrawals for

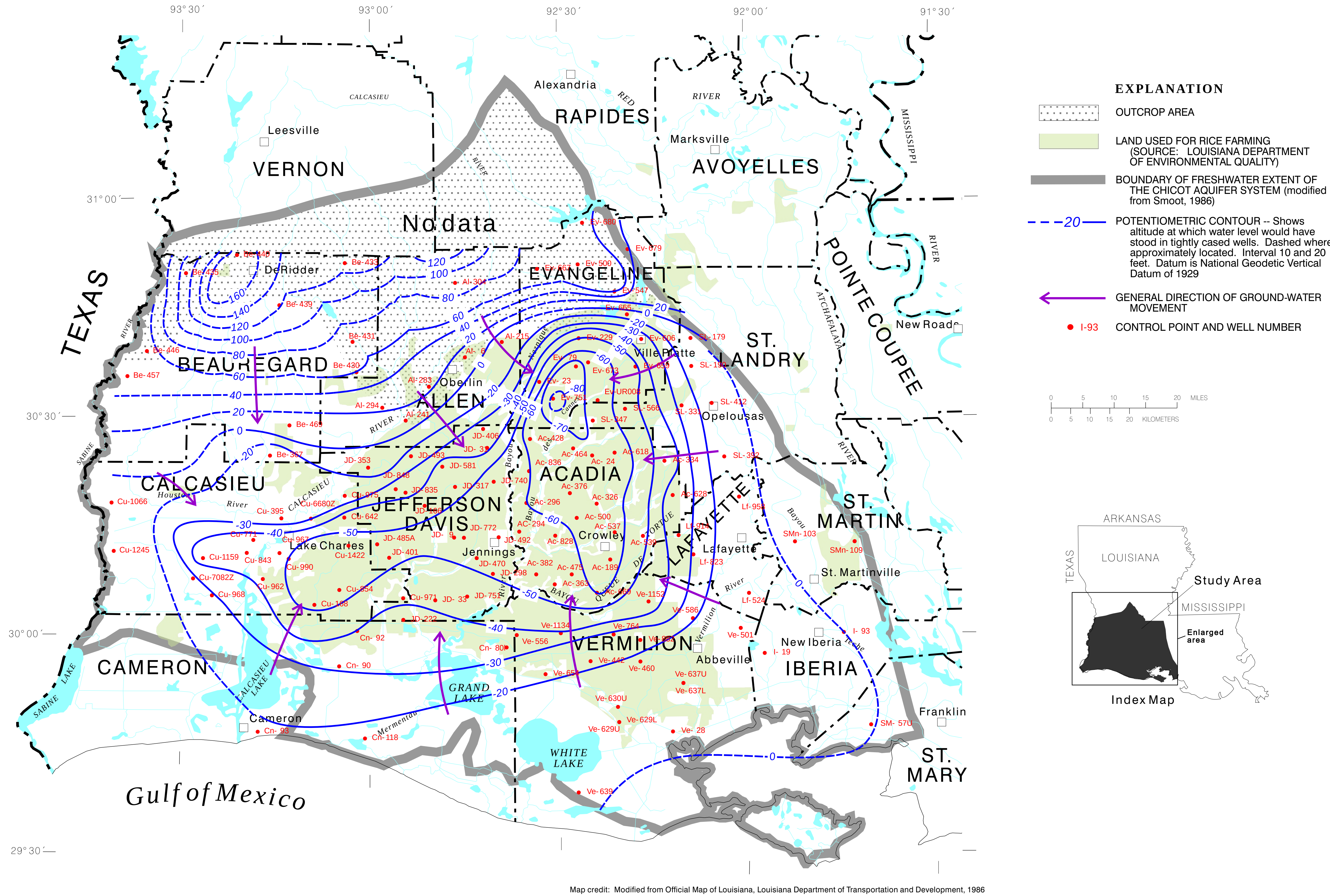


Figure 5. Potentiometric surface of the massive, upper, and "200-foot" sands of the Chicot aquifer system in southwestern Louisiana, June 2002.

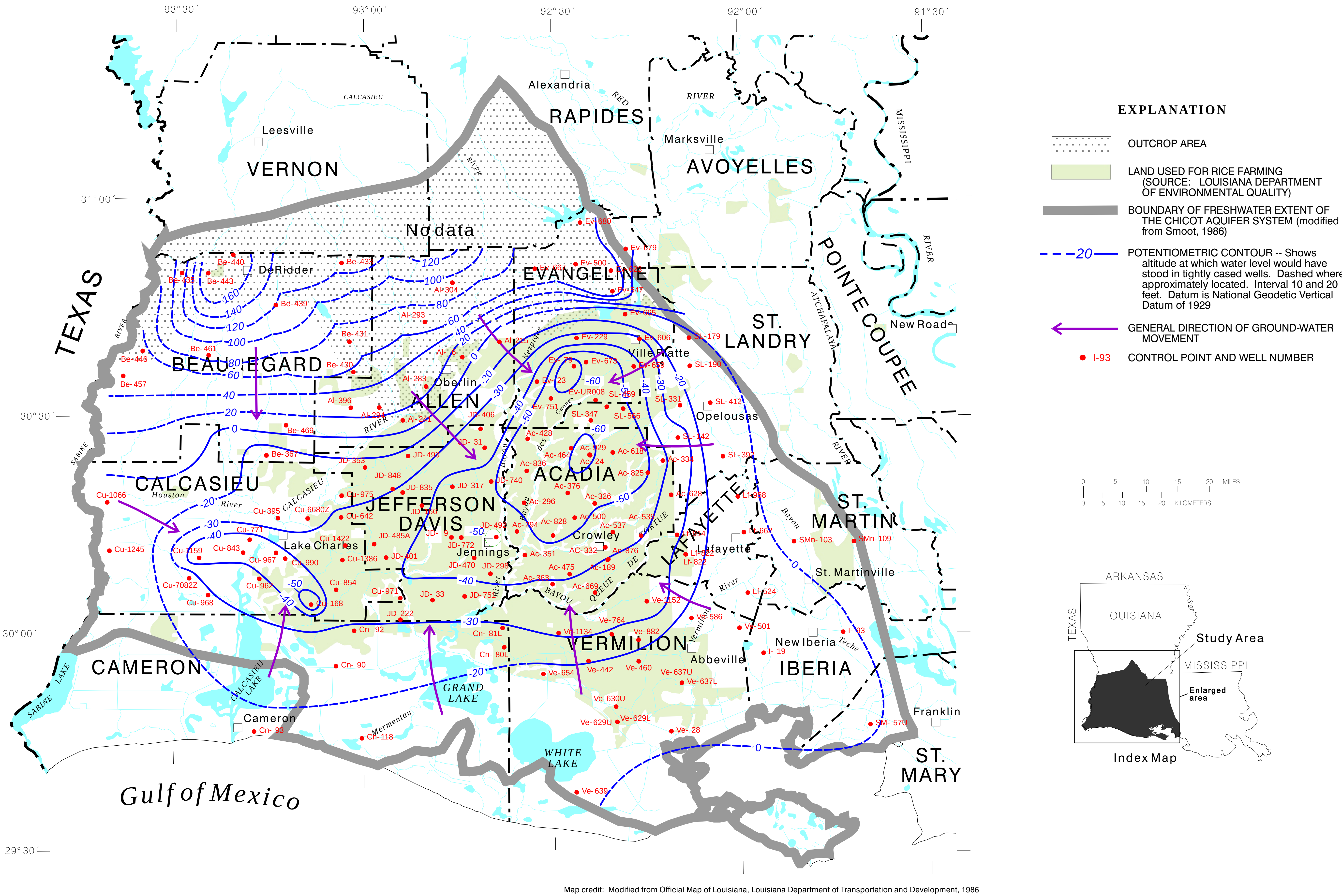
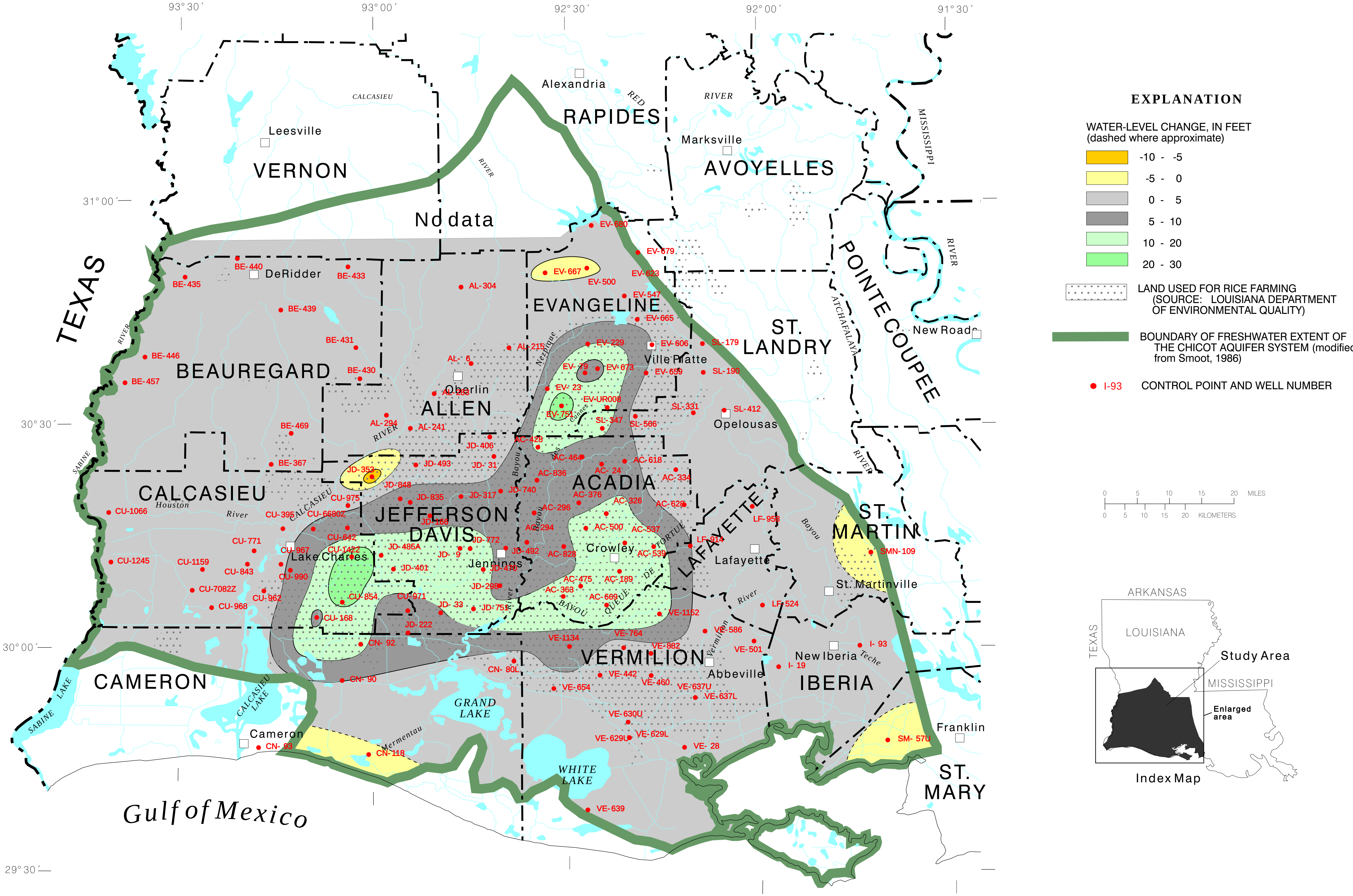


Figure 6. Potentiometric surface of the massive, upper, and "200-foot" sands of the Chicot aquifer system in southwestern Louisiana, January 2003.



Map credit: Modified from Official Map of Louisiana, Louisiana Department of Transportation and Development, 1986

Figure 7. Water-level change in the massive, upper, and “200-foot” sands of the Chicot aquifer system in southwestern Louisiana, June 2002 to January 2003.

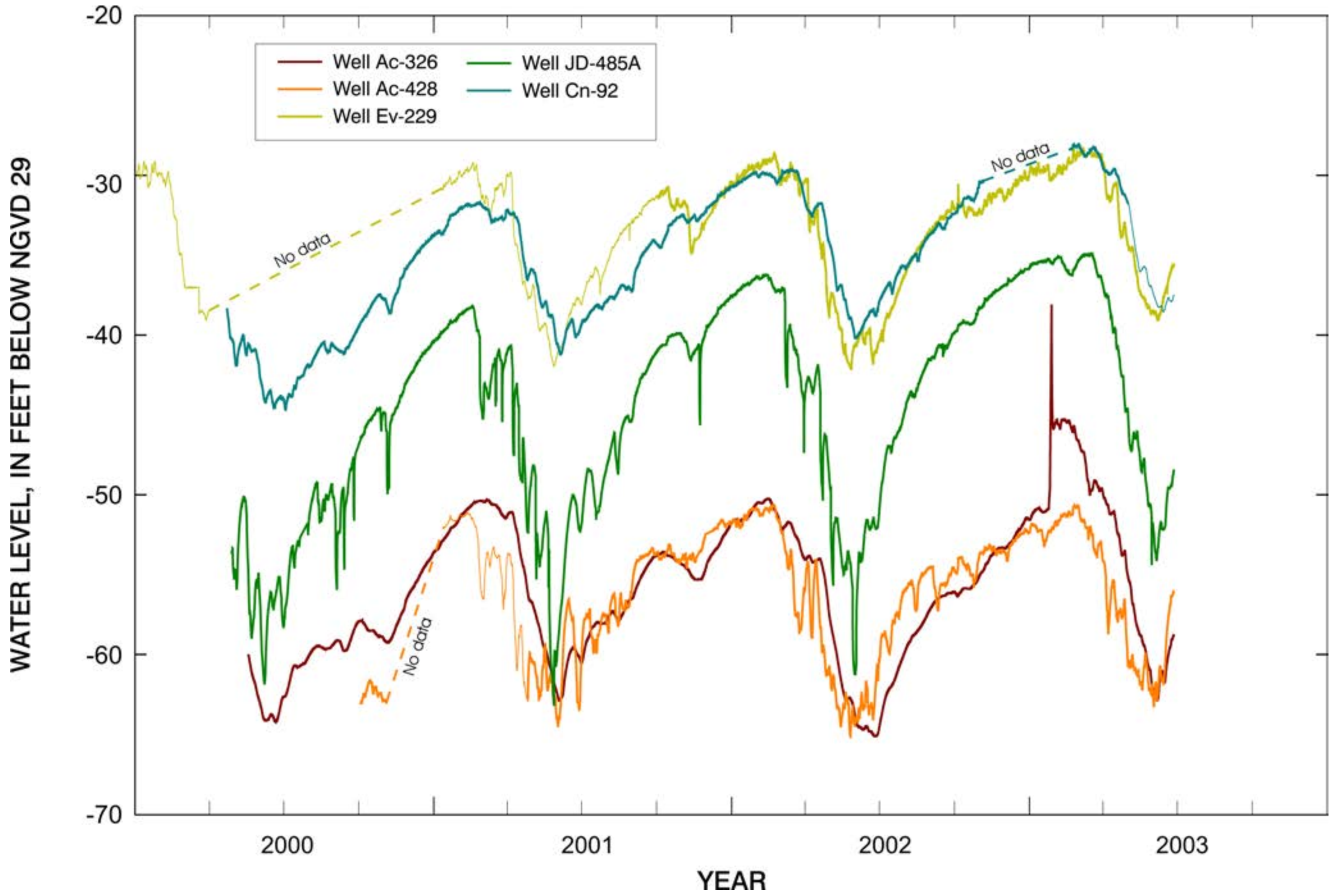


Figure 8. Hourly water levels at selected wells screened in the Chicot aquifer system in southwestern Louisiana, 2000-03 (see fig. 1 for well locations).

other purposes. The largest fluctuation of water levels, about 25 ft, was noted at well JD-485A. Water levels at this well probably are influenced by nearby active irrigation wells. Water levels fluctuated only about 10 ft annually at wells Ev-229 and Cn-92, which are located near the edge of the rice-farming area (fig. 1).

Specific Conductance

Specific conductance, as used in this report, is the primary indicator of saltwater (chloride concentration greater than 250 mg/L). This chloride concentration correlates to a specific conductance value of about 1,300 µS/cm in water from the Chicot aquifer system (fig. 9).

When used for irrigation, saltwater can inhibit rice growth and reduce grain yields (Grattan and others, 2002). Hill [n.d.] developed guidelines for using saltwater on rice in Louisiana and a table of commonly accepted tolerance of rice to selected saltwater concentrations (table 2). Hill indicates that water with a specific conductance value greater than about 2,000 µS/cm can adversely affect rice during early stages of development. Hill also indicates that continued use of irrigation water with a specific conductance value greater than about 1,000 µS/cm can cause a buildup of salt in the soil that could damage both crop and soil.

Concentrations of salt, as sodium chloride, commonly referred to as “total salts,” in parts per million and grains per gallon (table 2), are used by many farmers and agricultural agents in Louisiana. The concentration of total salts, in parts per million, is approximately equivalent to the concentration of total dissolved solids and is calculated by multiplying the specific conductance value, in microsiemens per centimeter, by 0.64 (E.R. Funderburg, Louisiana State University Agricultural Center, written commun., 2000). The concentration of total salts, in grains per gallon, can be calculated by dividing the specific conductance value by 26.56 or by dividing the concentration of total salts, in parts per million, by 17.14.

Data collected during the period 1943 to 2003 from 1,355 wells screened in the massive, upper, and “200-foot” sands of the Chicot aquifer system and the Atchafalaya aquifer were used to delineate areas having similar specific conductance values and determine areas where wells are affected by saltwater (fig. 10). Areas having similar specific conductance

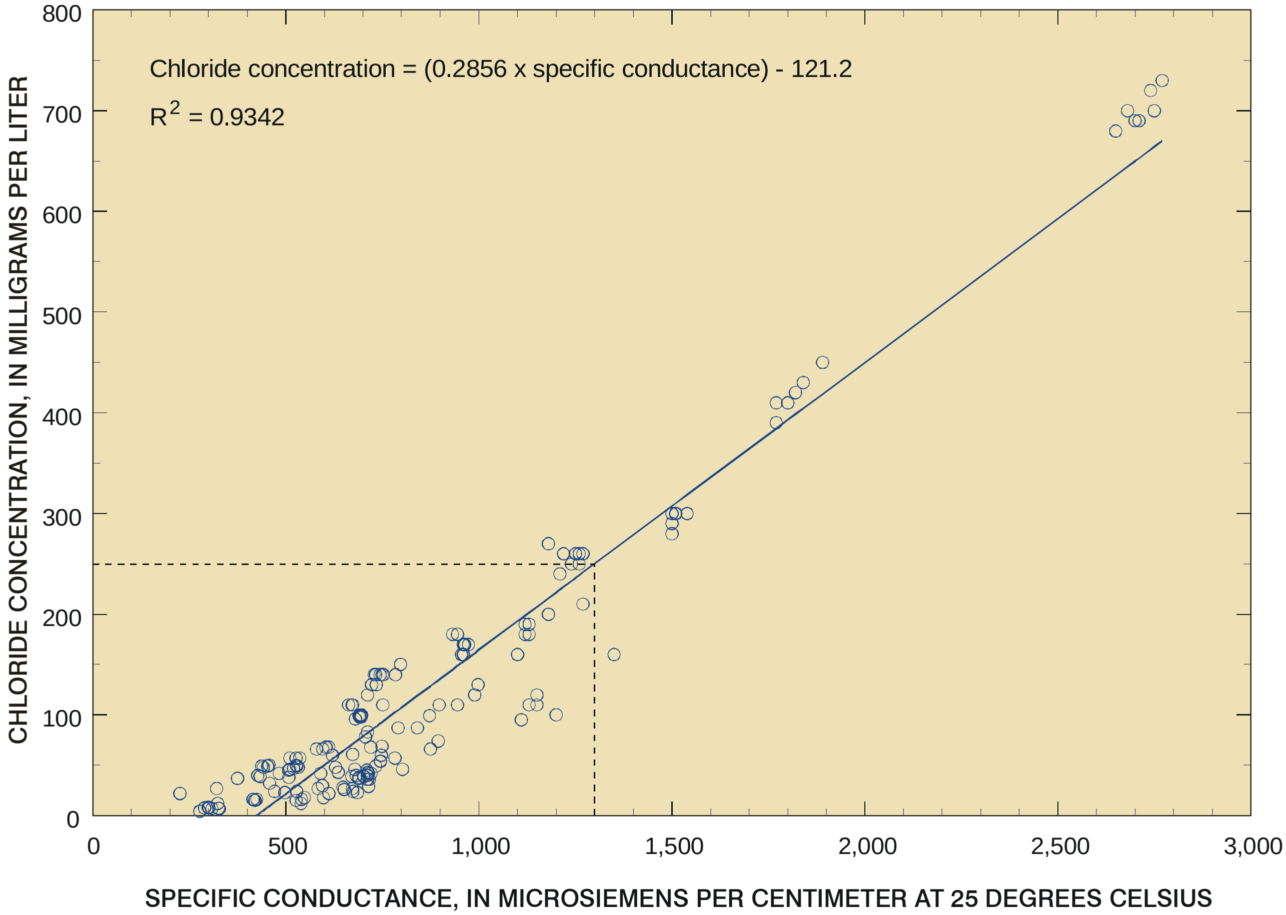


Figure 9. The relation between specific conductance values and chloride concentrations in the Chicot aquifer system in southwestern Louisiana.

Table 2. Commonly accepted tolerance of rice to selected saltwater concentrations (modified from Hill, [n.d]).

Specific conductance, in microsiemens per centimeter at 25 degrees Celsius	Salt, as sodium chloride, in parts per million	Salt, as sodium chloride, in grains per gallon	Stage of growth
938	600	35	Tolerable at all stages, not harmful.
2,031	1,300	75	Rarely harmful and only to seedlings after the soil is dry enough to crack. Tolerable from tillering on to heading.
2,656	1,700	100	Harmful before tillering. Tolerable from jointing to heading.
5,312	3,400	200	Harmful before booting. Tolerable from booting to heading.
7,969	5,100	300	Harmful to all stages of growth. This concentration stops growth and can only be used at the heading stage when the soil is saturated with freshwater.

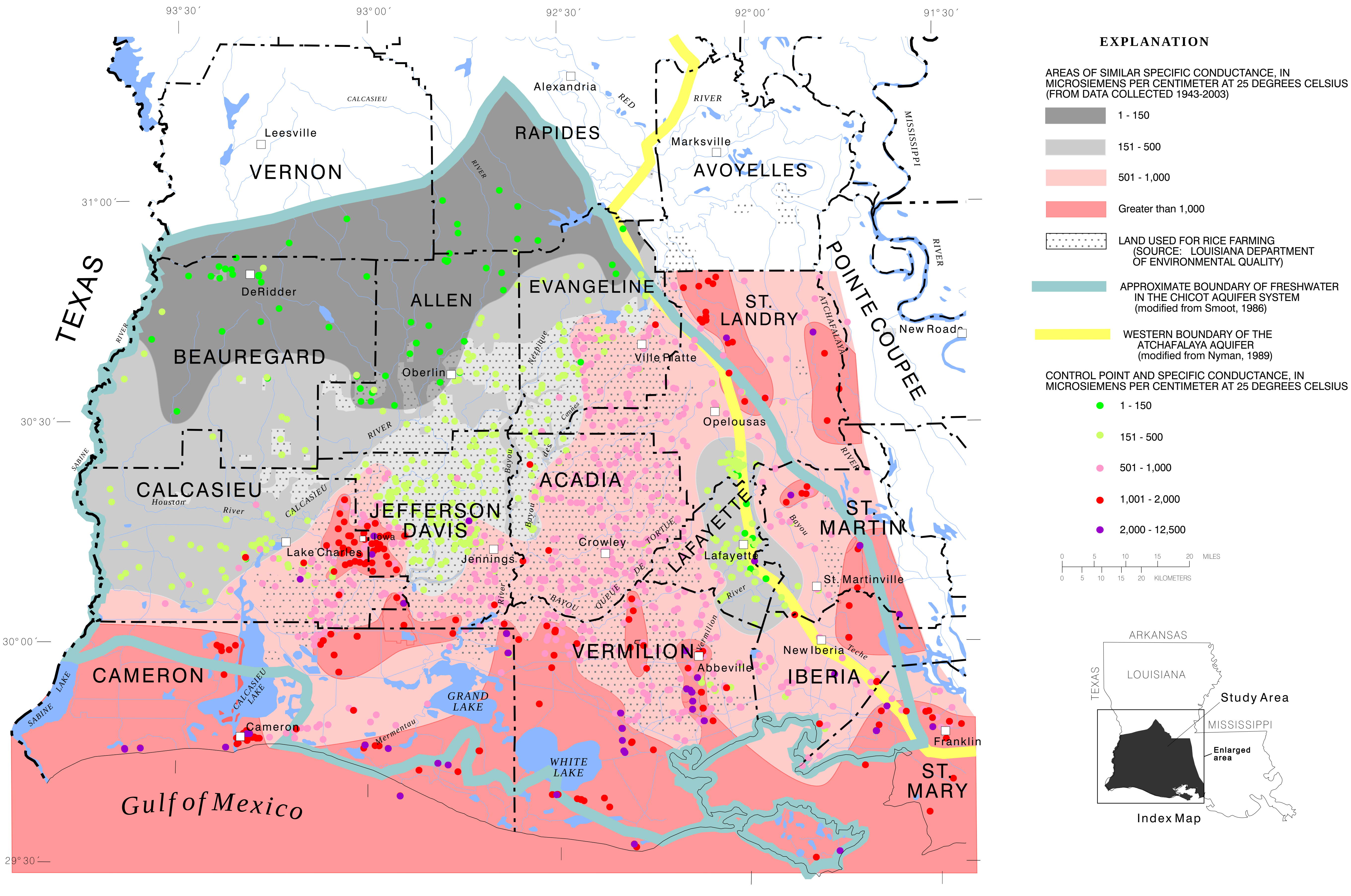


Figure 10. Specific conductance in the massive, upper, and “200-foot” sands of the Chicot aquifer system in southwestern Louisiana.

values were mapped based on the range of specific conductance values for water from the majority of wells sampled within an area. Specific conductance values at some wells are outside of the range shown for a particular area, but also are included in figure 10. For the purposes of this report, the maximum specific conductance value measured from a well was used when multiple measurements had been made for that well. Field specific conductance values were used when available; laboratory specific conductance values were used when field values were unavailable.

In and near the outcrop area (fig. 1), specific conductance values generally are less than 150 μS/cm (fig. 10). Specific conductance values increase south and east from the outcrop area. Specific conductance values generally range from 151 to 500 μS/cm in rice-farming areas of northwestern Acadia Parish, southeastern Allen Parish, western Evangeline Parish, and northern and central Jefferson Davis Parish. Specific conductance values generally range from 501 to 1,000 μS/cm in most of the remaining rice-farming areas. Specific conductance values often exceed 1,000 μS/cm in an area along the border between Calcasieu and Jefferson Davis Parishes near Iowa; parts of northeastern Cameron Parish; an area of northwestern and central St. Landry Parish; parts of Vermilion Parish; and several areas along the eastern boundary of the study area where the Chicot aquifer system merges with the Atchafalaya aquifer. The maximum specific conductance value, 12,100 μS/cm, is from a well in Cameron Parish.

Fresh ground water is available throughout much of Louisiana, but is underlain by saltwater at some depth. The maximum depth of freshwater in an area is called the base of freshwater. In much of southwestern Louisiana, the base of freshwater within the Chicot aquifer system occurs at depths greater than 800 ft below NGVD 29 (Harder and others, 1967, pl. 6). In coastal parishes, the base of freshwater occurs within the Chicot aquifer system at depths less than 400 ft below NGVD 29 in several areas (Harder and others, 1967, pl. 6; Nyman, 1984, pl. 2). Specific conductance in wells sampled in these areas generally exceeds 1,000 μS/cm (fig. 10). In parts of northwestern, central, and eastern St. Landry Parish, where the base of freshwater occurs at depths less than 200 ft below NGVD 29 (Harder and others, 1967, pl. 6; Hosman and others, 1970, pl. 1), specific conductance generally exceeds 1,000 μS/cm.

Where the base of freshwater occurs within an aquifer, two distinct layers may be formed because saltwater is denser than freshwater. Because of the density difference, the contact between the freshwater and saltwater within an aquifer may form a mixing zone or interface. In areas of the Chicot aquifer system where a freshwater-saltwater interface is present (Nyman, 1984), high-capacity wells pumping from the freshwater part of the aquifer can draw saltwater from the lower part of the aquifer. As pumping continues, an increasing proportion of water drawn into the well could come from the lower, more saline part of the aquifer (Nyman, 1984, p. 11). According to Nyman (1984, p. 11), this saltwater coning, also termed “upconing,” is the most common cause of wells pumping saltwater in southwestern Louisiana. Some factors affecting the rate of upconing include: (1) the depth from the bottom of the well screen to the base of the aquifer, (2) the pumping rate, (3) the duration of pumping, (4) the vertical permeability of the aquifer, (5) the thickness of the aquifer, and (6) the difference in density between the two waters (Nyman, 1984, p. 11). Decreasing the rate or duration of pumping and screening high-capacity wells as far above the base of freshwater as possible could reduce the potential for upconing saltwater.

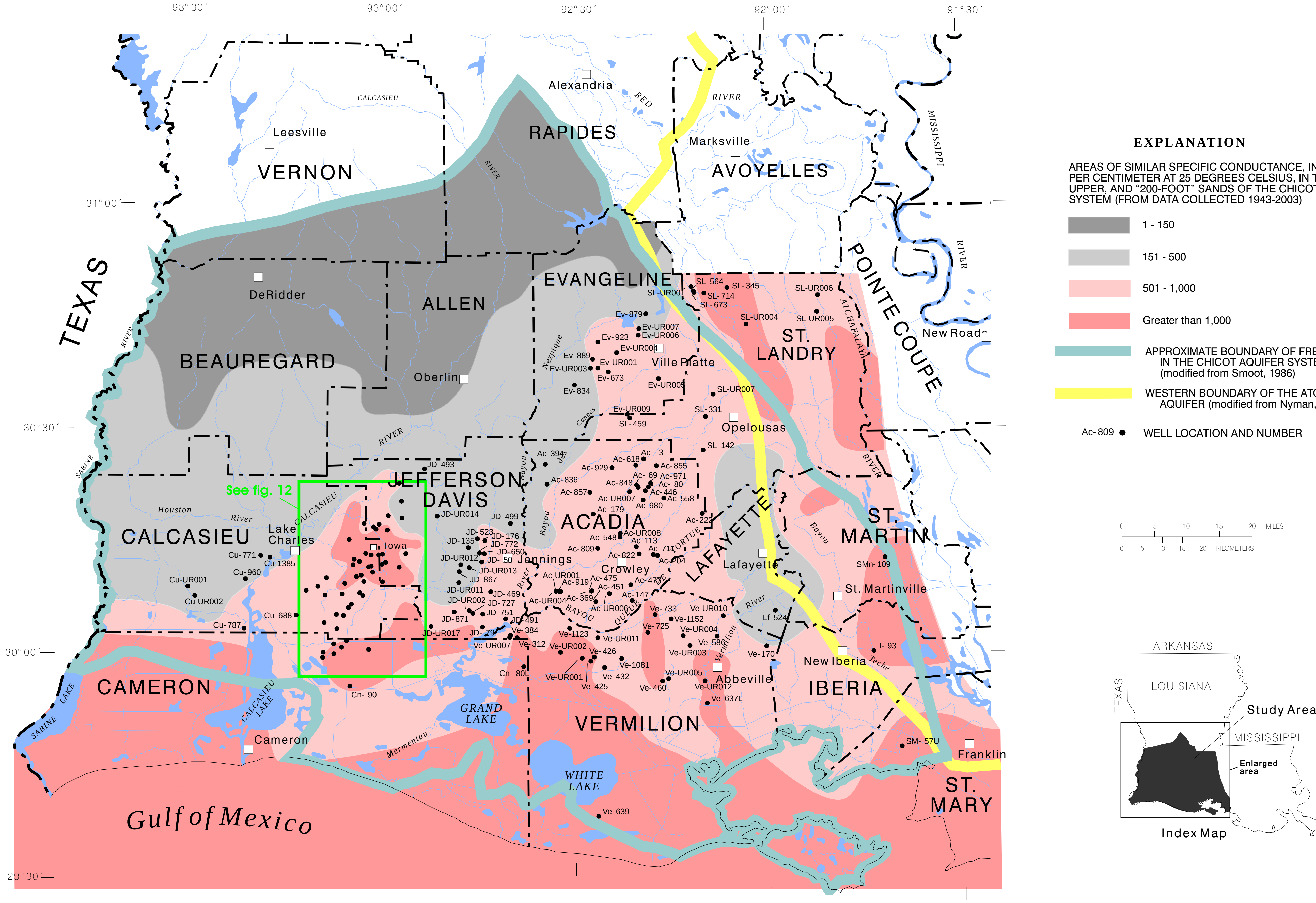
Specific conductance was measured in 521 water samples from 166 wells screened in the Chicot aquifer system or the Atchafalaya aquifer during 2000-03 to determine whether water from wells in areas where saltwater is present is becoming saltier. Most of the sampled wells were used for irrigation. Figures 11 and 12 show the locations of sampled wells; well construction and specific conductance data are included in table 3.

Well records from the Louisiana Department of Transportation and Development indicate that almost 100 percent of the 3,750 registered irrigation wells in the parishes where samples were collected are screened in the Chicot aquifer system or Atchafalaya aquifer (Z. “Bo” Bolourchi, Louisiana Department of Transportation and Development, written commun., 2003). Well-depth and screen-depth data were unavailable for 61 of the sampled wells. Although these wells are assumed to be screened in the Chicot aquifer system or the Atchafalaya aquifer because of their locations and use, the data are considered ancillary and specific conductance at these wells were not compared with specific conductance in wells of known depth.

Specific conductance values exceeded 1,000 μS/cm in water samples from wells in Calcasieu, Cameron, Jefferson Davis, St. Landry, St. Martin, St. Mary, and Vermilion Parishes. Specific conductance values exceeded 2,000 μS/cm in only two wells (table 3)—well Cu-UR003, which is an irrigation well located about 2 mi south of Iowa, and well Ve-637L, which is a USGS observation well used to monitor saltwater encroachment in east-central Vermilion Parish.

Only a few wells used for irrigation were sampled frequently enough throughout the period of the study to determine whether any trends in specific conductance were evident (table 3, fig. 13). For most of these wells, specific conductance values usually varied within a narrow range. However, specific conductance values increased steadily at well Cu-UR003 from 1,090 μS/cm in April 2000 to 2,860 μS/cm in April 2003 (table 3, fig. 13). Nearby wells, such as D-860 (table 3, fig. 13), did not show similar increases.

Specific conductance was measured hourly at two irrigation wells, Cu-1386 (2001-03) and Cn-196 (2000-03) (fig. 14). Specific conductance values were greater than 1,000 μS/cm in both wells, indicating the presence of saltwater near the wells. The data indicate that several short pumping events took place at each well during the rice-growing seasons over the 3-year period of study. Specific conductance values generally fluctu-



Map credit: Modified from Official Map of Louisiana, Louisiana Department of Transportation and Development, 1986

Figure 11. Location of wells sampled for specific conductance in southwestern Louisiana, 2000-03.

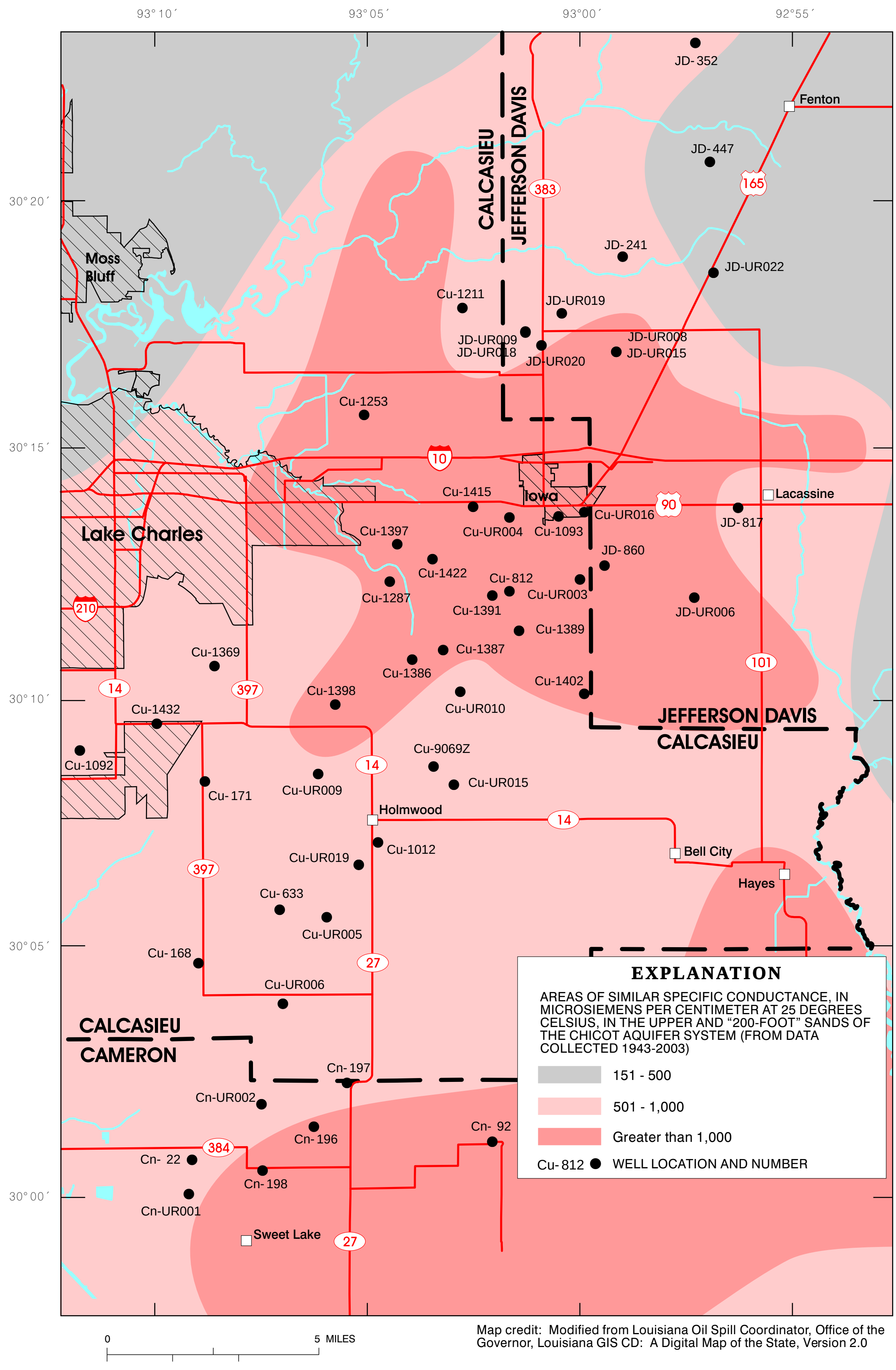


Figure 12. Location of wells sampled for specific conductance near Iowa, Louisiana, 2000-03.

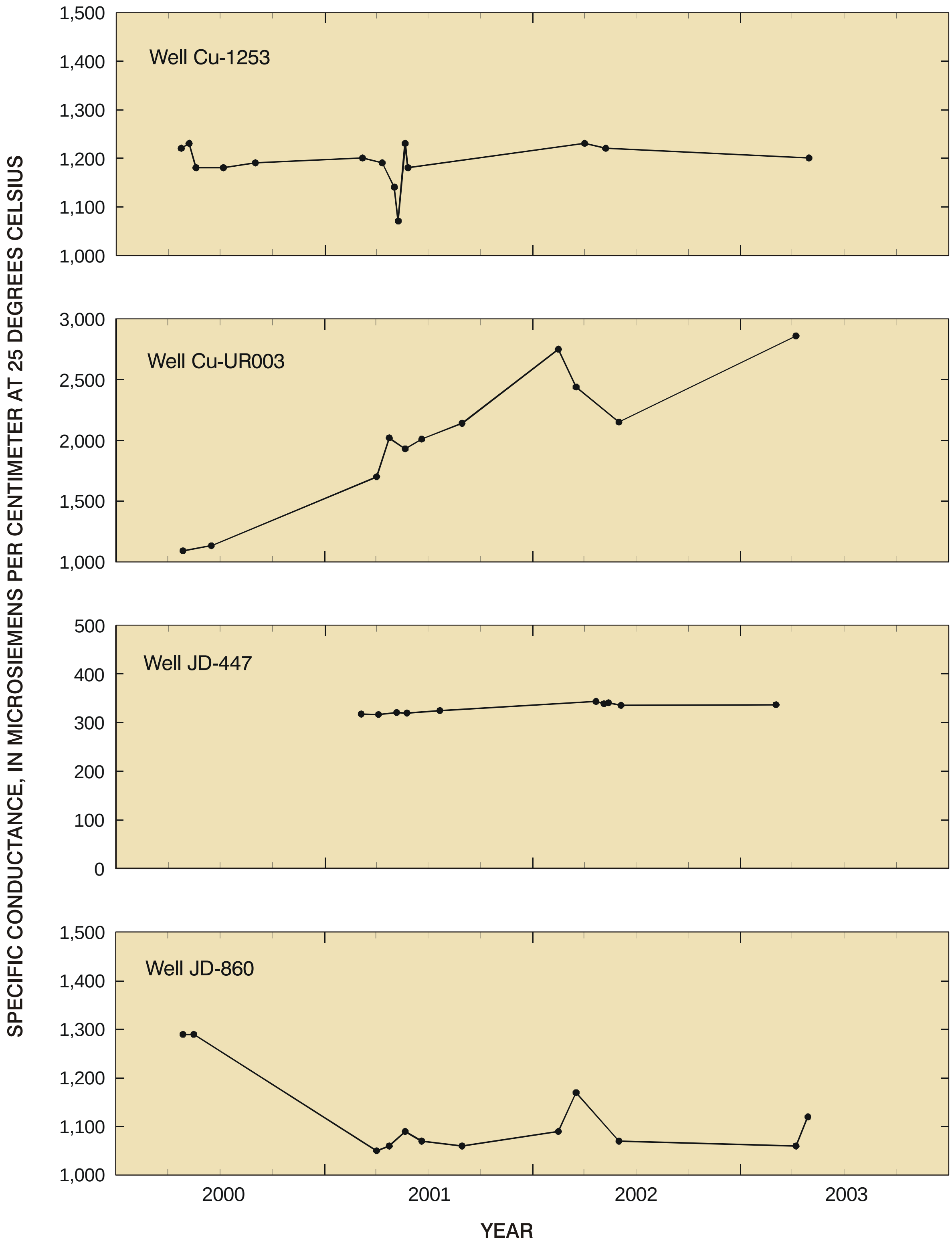


Figure 13. Specific conductance values at selected wells in southwestern Louisiana, 2000-03 (see figs. 11 and 12 for well locations).

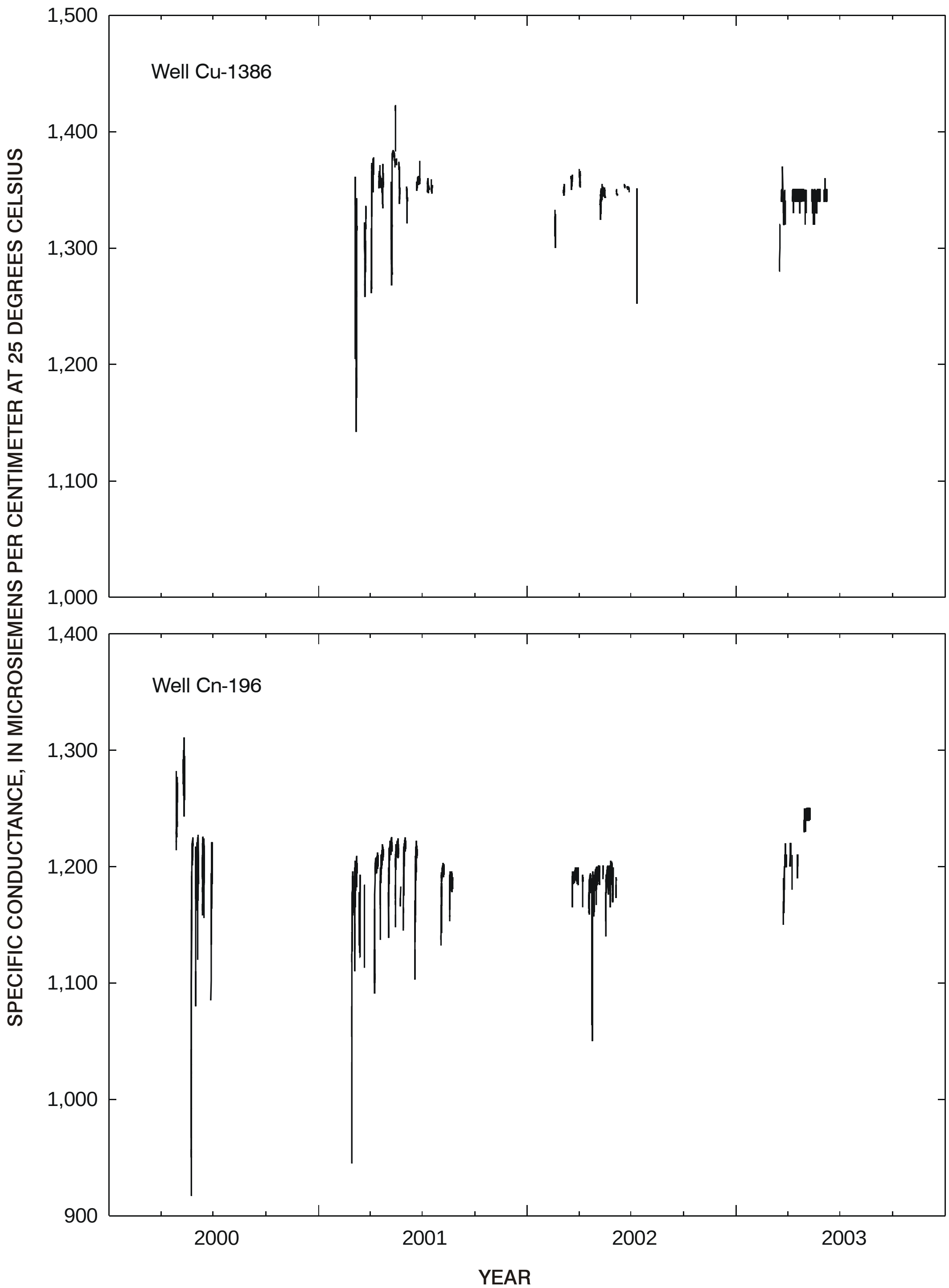


Figure 14. Hourly specific conductance values during pumping at selected wells screened in the Chicot aquifer system in southwestern Louisiana, 2000-03 (see fig. 1 for well locations).

ated about 150 μS/cm at both wells (fig. 14). Specific conductance values often increased 50 μS/cm or more in the wells during the first few hours of a pumping event, then usually stabilized to fluctuations within a range of 10 to 20 μS/cm. No long-term trends in the specific conductance were evident in either well during the periods monitored.

Summary

The Chicot aquifer system is the principal source of fresh ground-water supplies in southwestern Louisiana. Much of the area is rural and rice cultivation is the primary agricultural activity. Withdrawals from the aquifer system, primarily for rice irrigation, have caused water levels to decline as much as 100 feet beneath some rice-farming areas of southwestern Louisiana since the early 1900’s, creating an elongated cone of depression in the potentiometric surface over much of the region. About 540 million gallons per day were withdrawn from the Chicot aquifer system in southwestern Louisiana in 2000.

From 1990 to 2000, water levels at several observation wells screened in the Chicot aquifer system and located in rice-farming areas declined at an average rate of 1 to 2 feet per year. Some farmers and residents of southwestern Louisiana are concerned that water levels in the aquifer system may decline below pump intakes in their wells, leaving them without water. Water levels in some areas of the aquifer system also fluctuate seasonally, primarily in response to ground-water withdrawals for rice irrigation, and wells in these areas could be affected seasonally.

To determine the magnitude and areal extent of water-level declines caused by seasonal ground-water withdrawals for rice irrigation, water-level data were collected from 141 wells screened in the massive, upper, and “200-foot” sands of the Chicot aquifer system. These data were used to construct potentiometric-surface maps of the aquifer system for June 2002 and January 2003. During June 2002, water levels in the aquifer system were more than 40 feet below the National Geodetic Vertical Datum of 1929 (NGVD 29) in parts of Acadia, Calcasieu, Evangeline, and Jefferson Davis Parishes, in an area that generally coincides with rice-farming areas. The lowest water level, 80 feet below NGVD 29, was measured in southern Evangeline Parish. During January 2003, water levels were more than 30 feet below NGVD 29 in parts of Acadia, Calcasieu, Evangeline, and Jefferson Davis Parishes, in an area that generally coincides with rice-farming areas. The lowest water levels, more than 60 feet below NGVD 29, were measured in small areas of northern Acadia and southern Evangeline Parishes.

From June 2002 to January 2003, water levels recovered throughout most of the Chicot aquifer system in the study area in response to reduced withdrawals after the rice-growing season. Throughout much of the aquifer system, water levels recovered less than 5 feet. However, in most of Acadia and Jefferson Davis Parishes, southeastern Calcasieu Parish, and southern Evangeline Parish, in an area that generally coincides with rice-farming areas, water levels generally recovered between 5 and 20 feet. These water-level changes are typical of the magnitude and areal extent of seasonal water-level fluctuations that occur in the Chicot aquifer system in response to seasonal ground-water withdrawals for rice irrigation.

To determine the duration of seasonal water-level declines due to ground-water withdrawals for rice irrigation, water-levels in the Chicot aquifer system were measured hourly at five wells in the rice-farming area during 2000-03. Water levels at these wells typically declined between 10 and 25 feet, beginning in February or March and continuing through May or June. After June, water levels began to recover and generally continued to rise until seasonal ground-water withdrawals began the following year.

Saltwater in the Chicot aquifer system is a concern to farmers in southwestern Louisiana. Continued use of irrigation water having a specific conductance value greater than about 1,000 μS/cm (microsiemens per centimeter at 25 degrees Celsius) can cause a buildup of salt in the soil that could damage both crop and soil. The presence of saltwater has been documented in the aquifer system beneath coastal parishes and in some areas where the aquifer system merges with the stratigraphically adjacent Atchafalaya aquifer. Seasonal pumping for rice irrigation has altered flow directions in the Chicot aquifer system and can induce lateral or upward movement of saltwater. Some irrigation wells screened in the aquifer system may be affected by saltwater encroachment, especially during periods of increased pumping in response to drought conditions.

Data collected during the period 1943 to 2003 from 1,355 wells screened in the massive, upper, and “200-foot” sands of the Chicot aquifer system and the Atchafalaya aquifer were used to delineate areas having similar specific conductance values and determine areas where wells are affected by saltwater. Areas having similar specific conductance values were mapped based on the range of specific conductance values for water from the majority of wells sampled within an area.

Near the outcrop area, specific conductance values typically are less than 150 μS/cm. Specific conductance values increase south and east from the outcrop area. Specific conductance values generally range from 151 to 500 μS/cm in rice-farming areas of northwestern Acadia Parish, southeastern Allen Parish, western Evangeline Parish, and northern and central Jefferson Davis Parish. Specific conductance values generally range from 501 to 1,000 μS/cm in most of the remaining rice-farming areas. Specific conductance values often exceed 1,000 μS/cm in an area along the border between Calcasieu and Jefferson Davis Parishes near Iowa, Louisiana; parts of northeastern Cameron Parish; an area of northwestern and central St. Landry Parish; parts of Vermilion Parish; and several areas along the eastern boundary of the study area where the Chicot aquifer system merges with the Atchafalaya aquifer. The maximum specific conductance value, 12,100 μS/cm, is from a well in Cameron Parish.

In areas of the Chicot aquifer system where a freshwater-saltwater interface is present, high-capacity wells pumping from the freshwater portion of the aquifer can draw saltwater from the lower part of the aquifer. Screening high-capacity wells as far above the base of freshwater as possible could reduce the potential for upconing saltwater.

To document specific conductance in wells during 2000-03 and determine whether water from wells in areas where saltwater is present is becoming saltier, specific conductance was measured in 521 water samples from 166 wells screened in the Chicot aquifer system or the Atchafalaya aquifer during 2000-03. Specific conductance values exceeded 1,000 μS/cm in water samples from wells in Calcasieu, Cameron, St. Landry, St. Martin, St. Mary, and Vermilion Parishes. Specific conductance values exceeded 2,000 μS/cm in only two wells—an irrigation well located about 2 miles south of Iowa and a USGS observation well used to monitor saltwater encroachment in east-central Vermilion Parish. Specific conductance values increased steadily at one well, from 1,090 μS/cm in April 2000 to 2,860 μS/cm in April 2003. Nearby wells did not show similar increases.

Specific conductance was measured hourly at two irrigation wells during 2000-03. Specific conductance values were greater than 1,000 μS/cm in both wells, indicating the presence of saltwater near the wells. Specific conductance values generally fluctuated about 150 μS/cm at both wells, but no long-term trends in the specific conductance were evident in either well.

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Tables 1 and 3

Table 1. Water-level data used to construct potentiometric-surface maps for June 2002 and January 2003, and water-level change map, June 2002 to January 2003, in the massive, upper, and "200-foot" sands of the Chicot aquifer system in southwestern Louisiana.

[NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112CHCT, massive sand; 112CHCTU, upper sand; and 11202LC, "200-foot" sand. --, no data]

Well number	Aquifer code	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Water-level data						Water-level changes, June 2002 to January 2003 (feet)
				June 2002			January 2003			
				Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	
Acadia Parish										
Ac-24	112CHCT	41	284	6-05	109.45	-68.45	1-15	102.14	-61.14	7.31
Ac-189	112CHCTU	26	--	6-13	88.84	-63.00	1-14	64.34	-38.50	24.50
Ac-294	112CHCTU	25	260	6-05	78.99	-53.99	1-14	71.78	-46.78	7.21
Ac-296	112CHCTU	31	250	6-05	90.78	-59.78	1-14	82.52	-51.52	8.26
Ac-326	112CHCTU	25.80	202	6-23	90.92	-64.39	1-15	76.91	-51.11	13.28
Ac-332	112CHCTU	20	294	--	--	--	1-14	64.25	-44.25	--
Ac-334	112CHCT	40	300	6-05	87.60	-47.60	1-15	85.57	-45.57	2.03
Ac-351	113CHCTU	12	230	--	--	--	1-14	39.17	-27.17	--
Ac-363	112CHCTU	9	258	6-06	60.44	-51.44	1-14	48.26	-39.26	12.18
Ac-376	112CHCTU	32	250	6-06	96.67	-64.67	1-15	88.98	-56.98	7.69
Ac-382	112CHCTU	11	292	6-13	63.45	-52.45	--	--	--	--
Ac-428	112CHCT	42	203	6-06	105.02	-63.02	1-14	94.48	-52.48	10.54
Ac-464	112CHCTU	40	250	6-05	104.63	-64.63	1-14	99.69	-59.69	4.94
Ac-475	112CHCTU	14	286	6-06	69.43	-55.43	1-14	55.53	-41.53	13.90
Ac-500	112CHCTU	22	248	6-13	86.95	-64.95	1-15	73.90	-51.90	13.05
Ac-537	112CHCTU	25	211	6-04	87.71	-62.71	1-15	68.57	-43.57	19.14
Ac-539	112CHCTU	31	251	6-05	84.57	-53.57	1-14	72.21	-41.21	12.36
Ac-618	112CHCT	40	249	6-05	105.64	-65.64	1-15	97.23	-57.23	8.41
Ac-628	112CHCTU	35	250	6-05	72.81	-37.81	1-15	69.32	-34.32	3.49
Ac-669	112CHCTU	15	176	6-06	75.26	-60.26	1-14	52.02	-37.02	23.24

Table 1. Water-level data used to construct potentiometric-surface maps for June 2002 and January 2003, and water-level change map, June 2002 to January 2003, in the massive, upper, and "200-foot" sands of the Chicot aquifer system in southwestern Louisiana.—Continued

[NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112CHCT, massive sand; 112CHCTU, upper sand; and 11202LC, "200-foot" sand. --, no data]

Well number	Aquifer code	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Water-level data						Water-level changes, June 2002 to January 2003 (feet)
				June 2002			January 2003			
				Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	
				Acadia Parish—Continued						
Ac-825	112CHCT	43	266	--	--	--	1-15	93.28	-50.28	--
Ac-828	112CHCTU	21	302	6-06	78.80	-57.80	1-15	72.24	-51.24	6.56
Ac-836	112CHCT	37	275	6-13	96.77	-59.77	1-14	90.06	-53.06	6.71
Ac-876	112CHCTU	21	298	--	--	--	1-15	62.50	-41.50	--
Ac-929	112CHCTU	40	286	--	--	--	1-15	102.76	-62.76	--
				Allen Parish						
Al-6	112CHCT	80	--	6-06	68.18	11.82	1-09	66.02	13.98	2.16
Al-215	112CHCT	70	207	6-06	80.73	-10.73	1-09	80.55	-10.55	.18
Al-241	112CHCT	42.97	62	6-06	33.04	9.93	1-08	29.81	13.16	3.23
Al-283	112CHCT	62	93	6-06	39.47	22.53	1-09	37.95	24.05	1.52
Al-293	112CHCT	100	84	--	--	--	1-08	29.26	70.74	--
Al-294	112CHCT	48	142	6-06	24.30	23.70	1-08	22.30	25.70	2.00
Al-304	112CHCT	114	104	6-06	19.22	94.78	1-08	17.45	96.55	1.77
Al-396	112CHCT	57	315	--	--	--	1-08	29.53	27.47	--
				Beauregard Parish						
Be-367	112CHCT	45	455	6-04	70.38	-25.38	1-08	70.18	-25.18	.20
Be-430	112CHCT	120	123	6-06	60.68	59.32	1-08	60.70	59.30	-.02
Be-431	112CHCT	70	84	6-06	6.14	63.86	1-08	2.92	67.08	3.22
Be-433	112CHCT	132	82	6-04	7.85	124.15	1-08	5.14	126.86	2.71
Be-435	112CHCT	129	124	6-04	25.30	103.70	1-15	21.64	107.36	3.66

Table 1. Water-level data used to construct potentiometric-surface maps for June 2002 and January 2003, and water-level change map, June 2002 to January 2003, in the massive, upper, and "200-foot" sands of the Chicot aquifer system in southwestern Louisiana.—Continued

[NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112CHCT, massive sand; 112CHCTU, upper sand; and 11202LC, "200-foot" sand. --, no data]

Well number	Aquifer code	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Water-level data						Water-level changes, June 2002 to January 2003 (feet)
				June 2002			January 2003			
				Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	
Beauregard Parish—Continued										
Be-439	112CHCT	169	189	6-04	48.06	120.94	1-08	47.37	121.63	.69
Be-440	112CHCT	212	169	6-04	45.72	166.28	1-15	44.10	167.90	1.62
Be-443	112CHCT	206	164	--	--	--	1-15	36.10	169.90	--
Be-446	112CHCT	83	157	6-04	25.30	57.70	1-07	23.80	59.20	1.50
Be-457	112CHCT	95	155	6-04	48.23	46.77	1-07	43.99	51.01	4.24
Be-461	112CHCT	140	228	--	--	--	1-07	56.90	83.10	--
Be-469	112CHCT	84	380	6-04	71.84	12.16	1-08	69.62	14.38	2.22
Calcasieu Parish										
Cu-168	11202LC	7.81	375	6-05	59.31	-51.50	1-07	57.98	-50.17	1.33
Cu-395	11202LC	12	200	6-04	38.00	-26.00	1-06	36.93	-24.93	1.07
Cu-642	11202LC	19	287	6-06	62.70	-43.70	1-08	55.08	-36.08	7.62
Cu-771	11202LC	17.76	241	6-05	61.02	-43.26	1-06	59.15	-41.39	1.87
Cu-843	11202LC	12	205	6-05	54.01	-42.01	1-07	52.50	-40.50	1.51
Cu-854	11202LC	20	430	6-05	73.37	-53.37	1-07	52.03	-32.03	21.34
Cu-962	11202LC	11	287	6-05	52.48	-41.48	1-06	49.62	-38.62	2.86
Cu-967	11202LC	12	240	6-05	57.08	-45.08	1-06	54.31	-42.31	2.77
Cu-968	11202LC	10	276	6-05	39.53	-29.53	1-07	39.27	-29.27	.26
Cu-971	112CHCTU	5	500	6-07	46.29	-41.29	1-09	41.05	-36.05	5.24
Cu-975	11202LC	20	237	6-06	47.30	-27.30	1-08	42.65	-22.65	4.65

Table 1. Water-level data used to construct potentiometric-surface maps for June 2002 and January 2003, and water-level change map, June 2002 to January 2003, in the massive, upper, and "200-foot" sands of the Chicot aquifer system in southwestern Louisiana.—Continued

[NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112CHCT, massive sand; 112CHCTU, upper sand; and 11202LC, "200-foot" sand. --, no data]

Well number	Aquifer code	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Water-level data						Water-level changes, June 2002 to January 2003 (feet)
				June 2002			January 2003			
				Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	
Calcasieu Parish—Continued										
Cu-990	11202LC	14	183	6-05	64.13	-50.13	1-06	58.74	-44.74	5.39
Cu-1066	11202LC	25	255	6-04	33.65	-8.65	1-07	30.49	-5.49	3.16
Cu-1159	11202LC	13	280	6-05	58.15	-45.15	1-07	57.72	-44.72	.43
Cu-1245	11202LC	11	136	6-04	15.39	-4.39	1-07	12.44	-1.44	2.95
Cu-1386	11202LC	24	325	--	--	--	1-07	59.90	-35.90	--
Cu-1422	11202LC	22	262	6-14	80.69	-58.69	1-07	57.77	-35.77	22.92
Cu-6680Z	11202LC	11	170	6-04	40.72	-29.72	1-08	36.63	-25.63	4.09
Cu-7082Z	11202LC	13	260	6-05	42.39	-29.39	1-07	41.74	-28.74	.65
Cameron Parish										
Cn-80L	112CHCTU	4.73	481	6-14	37.37	-32.64	1-10	31.70	-26.97	2.67
Cn-81L	112CHCTU	4.45	478	--	--	--	1-10	33.71	-29.26	--
Cn-90	11202LC	3.19	396	6-05	34.61	-31.42	1-07	29.22	-26.03	5.39
Cn-92	11202LC	5.50	443	6-05	45.35	-39.85	1-07	34.70	-29.20	10.65
Cn-93	112CHCTU	3.76	360	6-05	21.76	-18.00	1-07	22.33	-18.57	-.57
Cn-118	112CHCTU	5	638	6-05	21.82	-16.82	1-07	22.19	-17.19	-.37
Evngeline Parish										
Ev-23	112CHCT	51.06	360	6-05	103.23	-52.17	1-08	93.04	-41.98	10.19
Ev-79	112CHCT	55	250	6-04	126.62	-71.62	1-07	118.64	-63.64	7.98
Ev-229	112CHCT	65.66	231	6-04	105.73	-40.07	1-07	95.71	-30.05	10.02
Ev-500	112CHCT	117.52	120	6-04	50.11	67.41	1-07	50.41	67.11	-.30

Table 1. Water-level data used to construct potentiometric-surface maps for June 2002 and January 2003, and water-level change map, June 2002 to January 2003, in the massive, upper, and "200-foot" sands of the Chicot aquifer system in southwestern Louisiana.—Continued

[NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112CHCT, massive sand; 112CHCTU, upper sand; and 11202LC, "200-foot" sand. --, no data]

Well number	Aquifer code	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Water-level data						Water-level changes, June 2002 to January 2003 (feet)
				June 2002			January 2003			
				Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	
Evngeline Parish—Continued										
Ev-547	112CHCT	113.38	80	6-04	53.61	59.77	1-06	44.77	68.61	8.84
Ev-606	112CHCT	75	255	6-05	110.29	-35.29	1-08	105.82	-30.82	4.47
Ev-623	112CHCT	137.20	96	--	--	--	1-07	59.44	77.76	--
Ev-659	112CHCT	60.52	252	6-05	111.33	-50.81	1-07	105.89	-45.37	5.44
Ev-665	112CHCT	59.29	100	6-04	70.91	-11.62	1-06	67.49	-8.20	3.42
Ev-667	112CHCT	122.20	91.50	6-04	48.81	73.39	1-07	49.04	73.16	-.23
Ev-673	112CHCT	60	247	6-05	126.16	-66.16	1-08	119.96	-59.96	6.20
Ev-679	112CHCT	46	70	6-04	5.27	40.73	1-07	4.00	42.00	1.27
Ev-680	112CHCT	120	89	6-04	55.76	64.24	1-07	55.28	64.72	.48
Ev-751	112CHCT	53	275	6-05	133.49	-80.49	1-08	109.59	-56.59	23.90
Ev-UR008	--	56	--	6-12	123.68	-67.68	1-09	109.91	-53.91	13.77
Ev-UR009	--	58	--	--	--	--	1-09	106.19	-48.19	--
Iberia Parish										
I-19	112CHCTU	9.72	460	6-04	18.16	-8.44	1-13	15.68	-5.96	2.48
I-93	112CHCTU	18.53	585	6-04	19.66	-1.13	1-13	19.55	-1.02	.11
Jefferson Davis Parish										
JD-9	112CHCTU	24.10	318	6-11	84.70	-60.60	1-09	68.60	-44.50	16.10
JD-31	112CHCT	50	250	6-10	89.51	-39.51	1-09	87.96	-37.96	1.55
JD-33	112CHCTU	7.18	350	6-07	49.67	-42.49	1-10	40.07	-32.89	9.60

Table 1. Water-level data used to construct potentiometric-surface maps for June 2002 and January 2003, and water-level change map, June 2002 to January 2003, in the massive, upper, and "200-foot" sands of the Chicot aquifer system in southwestern Louisiana.—Continued

[NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112CHCT, massive sand; 112CHCTU, upper sand; and 11202LC, "200-foot" sand. --, no data]

Well number	Aquifer code	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Water-level data						Water-level changes, June 2002 to January 2003 (feet)
				June 2002			January 2003			
				Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	
				Jefferson Davis Parish—Continued						
JD-166	112CHCTU	2	--	6-11	84.63	-46.63	1-09	76.88	-38.88	7.75
JD-222	112CHCTU	4.61	300	6-07	41.42	-36.81	1-09	35.38	-30.77	6.04
JD-298	112CHCTU	15	297	6-14	66.08	-51.08	1-10	59.52	-44.52	6.56
JD-317	112CHCT	42.27	289	6-11	91.18	-48.91	1-09	85.38	-43.11	5.80
JD-353	112CHCT	25	300	6-06	40.70	-15.70	1-08	46.49	-21.49	-5.79
JD-401	112CHCTU	14	282	6-07	66.90	-52.90	1-09	50.33	-36.33	16.57
JD-406	112CHCT	50	450	6-10	83.91	-33.91	1-09	83.26	-33.26	.65
JD-470	112CHCTU	10	325	6-07	65.08	-55.08	1-10	52.68	-42.68	12.40
JD-485A	112CHCTU	21.36	290	6-07	75.52	-54.16	1-09	56.79	-35.43	18.73
JD-492	112CHCTU	25	613	6-07	85.32	-60.32	1-10	77.90	-52.90	7.42
JD-493	112CHCT	37.95	220	6-14	60.55	-22.60	1-09	59.04	-21.09	1.51
JD-581	112CHCT	35	--	6-11	88.44	-53.44	--	--	--	--
JD-740	112CHCT	35	264	6-10	89.67	-54.67	1-09	84.20	-49.20	5.47
JD-751	112CHCTU	10	193	6-14	53.30	-43.30	1-10	41.96	-31.96	11.34
JD-772	112CHCTU	27	340	6-11	84.93	-57.93	1-09	68.27	-41.27	16.66
JD-835	112CHCTU	31	280	6-14	70.83	-39.83	1-09	64.47	-33.47	6.36
JD-848	112CHCTU	32	243	6-06	69.84	-37.84	1-09	61.38	-29.38	8.46

Table 1. Water-level data used to construct potentiometric-surface maps for June 2002 and January 2003, and water-level change map, June 2002 to January 2003, in the massive, upper, and "200-foot" sands of the Chicot aquifer system in southwestern Louisiana.—Continued

[NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112CHCT, massive sand; 112CHCTU, upper sand; and 11202LC, "200-foot" sand. --, no data]

Well number	Aquifer code	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Water-level data						Water-level changes, June 2002 to January 2003 (feet)
				June 2002			January 2003			
				Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	
Lafayette Parish										
Lf-524	112CHCTU	25	174	6-04	30.80	-5.80	1-13	29.97	-4.97	.83
Lf-662	112CHCTU	40.37	152	--	--	--	1-13	49.58	-9.21	--
Lf-822	112CHCTU	30	--	--	--	--	1-14	54.80	-24.80	--
Lf-823	112CHCTU	30	363	6-04	59.58	-29.58	--	--	--	--
Lf-914	112CHCTU	30	250	6-13	67.43	-37.43	1-14	62.79	-32.79	4.64
Lf-958	112CHCTU	50	115	6-05	53.53	-3.53	1-13	53.37	-3.37	.16
St. Landry Parish										
SL-142	112CHCT	50	235	--	--	--	1-09	85.58	-35.58	--
SL-179	112CHCT	55.23	94	6-04	58.47	-3.24	1-06	58.75	-3.52	-0.28
SL-190	112CHCT	74.36	175	6-06	87.97	-13.61	1-06	87.54	-13.18	.43
SL-331	112CHCT	62	--	6-06	89.95	-27.95	1-09	89.51	-27.51	.44
SL-347	112CHCT	50	300	6-06	118.38	-68.38	1-09	107.82	-57.82	10.56
SL-392	112CHCT	46.74	126	6-06	56.44	-9.70	1-10	95.39	-48.65	-38.95
SL-412	112CHCT	70	302	6-06	80.27	-10.27	1-10	79.65	-9.65	.62
SL-566	112CHCT	51	250	6-06	104.13	-53.13	1-10	102.68	-51.68	1.45
St. Martin Parish										
SMn-109	112CHCTU	11.34	375	6-04	3.15	8.19	1-13	5.76	5.58	-2.61
St. Mary Parish										
SM-57U	112CHCTU	8.72	638	6-04	10.05	-1.33	1-13	10.52	-1.80	-.47

Table 1. Water-level data used to construct potentiometric-surface maps for June 2002 and January 2003, and water-level change map, June 2002 to January 2003, in the massive, upper, and "200-foot" sands of the Chicot aquifer system in southwestern Louisiana.—Continued

[NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112CHCT, massive sand; 112CHCTU, upper sand; and 11202LC, "200-foot" sand. --, no data]

Well number	Aquifer code	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Water-level data						Water-level changes, June 2002 to January 2003 (feet)
				June 2002			January 2003			
				Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	Date measured	Depth to water level (feet below land surface)	Altitude of water level (feet relative to NGVD 29)	
Vermilion Parish										
Ve-28	112CHCTU	6.74	260	6-10	13.23	-6.49	1-15	12.47	-5.73	.76
Ve-442	112CHCTU	5.42	281	6-11	31.23	-25.81	1-14	25.81	-20.39	5.42
Ve-460	112CHCTU	9.78	300	6-11	26.63	-16.85	1-14	25.64	-15.86	.99
Ve-501	112CHCTU	22	227	6-04	29.61	-7.99	1-13	28.46	-6.84	1.15
Ve-556	112CHCTU	6	263	6-11	40.91	-34.91	--	--	--	--
Ve-586	112CHCTU	15.40	259	6-11	36.00	-20.60	1-15	34.29	-18.89	1.71
Ve-629L	112CHCTU	1.79	487	6-10	9.25	-7.46	1-15	7.89	-6.19	1.27
Ve-629U	112CHCTU	1.79	457	6-10	8.16	-6.37	1-15	6.87	-5.08	1.29
Ve-630U	112CHCTU	4.75	528	6-10	14.95	-10.20	1-15	13.37	-8.62	1.58
Ve-637L	112CHCTU	4.06	243	6-10	14.54	-10.48	1-15	13.43	-9.37	1.11
Ve-637U	112CHCTU	4.06	198	6-10	14.15	-10.09	1-15	13.32	-9.26	.83
Ve-639	112CHCTU	5.84	608	6-10	10.73	-4.89	1-15	10.72	-4.88	.01
Ve-654	112CHCTU	9.60	267	6-11	30.80	-21.20	1-14	26.65	-17.05	4.15
Ve-764	112CHCTU	15	250	6-11	44.50	-29.50	1-14	44.34	-29.34	.16
Ve-882	112CHCTU	10	279	6-11	39.79	-29.79	1-14	36.50	-26.50	3.29
Ve-1134	112CHCTU	5	190	6-11	44.91	-39.91	1-14	35.99	-30.99	8.92
Ve-1152	112CHCTU	10	235	6-11	57.57	-47.57	1-14	47.07	-37.07	10.50

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
						Acadia Parish						
Ac-3	302623	921939	112CHCT	I	50	338	--	--	6-05-2002	912	897	110
Ac-69	302236	922029	112CHCT	I	43	--	--	--	6-05-2002	699	682	40
Ac-80	302240	921856	112CHCT	I	--	--	--	--	5-22-2002	744	--	--
Ac-113	301441	922050	112CHCTU	I	25	331	--	--	5-03-2001	697	674	24
Ac-147	300731	922131	112CHCTU	I	17.78	298	--	--	6-28-2000	845	--	--
									7-18-2000	831	--	--
									8-14-2000	849	--	--
									8-30-2000	839	--	--
									10-09-2000	844	--	--
									10-24-2000	852	--	--
									4-05-2001	808	--	--
									5-02-2001	860	841	87
									5-10-2001	827	--	--
									10-08-2001	858	--	--
Ac-179	301904	922725	112CHCTU	I	34.61	313	--	--	6-06-2002	626	626	54
Ac-204	301323	921723	112CHCTU	I	--	--	--	--	6-01-2000	602	--	--
									6-16-2000	555	--	--
									6-28-2000	578	--	--
									7-15-2000	602	--	--
									8-02-2000	608	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Acadia Parish—Continued												
Ac-204	301323	921723	112CHCTU	I	--	--			8-15-2000	609	--	--
									9-03-2000	610	--	--
									9-16-2000	606	--	--
									12-11-2000	606	--	--
									5-02-2001	619	612	22
Ac-222	301904	921040	112CHCTU	I	36	--	--	--	6-05-2002	554	539	12
Ac-369	300850	922742	112CHCTU	I	15	280	200	280	6-06-2002	727	711	36
Ac-394	302545	923445	112CHCT	I	36	287	197.24	283.66	5-30-2002	386	375	37
Ac-446	302209	921924	112CHCT	I	40	234	167	234	5-22-2002	735	--	--
Ac-451	300740	922650	112CHCTU	N	14	293	212.5	293.4	3-15-2000	762	793	41
									9-13-2000	771	803	41
									3-09-2001	771	771	39
									9-19-2001	765	792	38
									4-09-2002	770	794	42
									9-13-2002	759	799	40
									3-28-2003	761	799	40
Ac-475	300848	922746	112CHCTU	I	14	286	226.4	286.4	5-16-2001	735	716	36
Ac-477	300937	922144	112CHCTU	I	20	269	208.95	269	5-16-2001	700	672	27
Ac-548	301558	922321	112CHCTU	I	25	278	208	278	5-10-2001	676	--	--
									5-24-2001	678	--	--
									6-19-2001	684	--	--
									7-12-2001	684	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Acadia Parish—Continued												
Ac-558	302109	921634	112CHCTU	I	42	205	175	205	5-30-2002	--	528	24
Ac-618	302533	922051	112CHCT	I	40	249	209	249	5-30-2002	670	636	43
Ac-711	301337	921814	112CHCTU	I	25	260	238	260	5-02-2001	665	651	26
Ac-809	301430	922647	112CHCTU	I	23	235	160	220	5-15-2001	758	747	60
Ac-822	301343	922024	112CHCTU	I	25	300	--	--	6-05-2000	686	--	--
									6-20-2000	698	--	--
									6-28-2000	569	--	--
									7-15-2000	700	--	--
									8-02-2000	679	--	--
									8-15-2000	642	--	--
									9-01-2000	700	--	--
									9-16-2000	713	--	--
									12-11-2000	701	--	--
									5-02-2001	719	714	29
Ac-836	302304	923431	112CHCT	I	37	275	--	--	5-31-2002	444	427	40
									6-06-2002	444	434	39
Ac-848	302254	922045	112CHCT	I	42	248	168	241	5-15-2001	692	671	39
Ac-855	302528	921742	112CHCT	I	45	253	179	252	5-30-2002	727	710	45
Ac-857	302158	922756	112CHCT	I	41	272	174	271	5-31-2002	771	706	78
Ac-919	300846	923227	112CHCTU	I	10	274	202	273	4-30-2003	806	791	87
Ac-929	302515	922431	112CHCTU	I	40	285	203	285	5-15-2001	690	673	61
Ac-971	302309	921835	--	I	46	--	--	--	5-22-2002	750	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Acadia Parish—Continued												
Ac-980	302055	921946	112CHCTU	I	36	276	179	274	5-22-2002	727	--	--
Ac-UR001	300847	923245	--	I	10	--	--	--	5-11-2000	847	--	--
									5-20-2000	787	--	--
Ac-UR004	300847	923312	--	I	11	--	--	--	6-28-2000	823	--	--
									7-29-2000	814	--	--
Ac-UR006	300827	922501	--	I	--	--	--	--	6-28-2000	682	--	--
									7-18-2000	677	--	--
									8-14-2000	690	--	--
									8-30-2000	685	--	--
									10-09-2000	677	--	--
									10-24-2000	687	--	--
									4-05-2001	676	--	--
									5-02-2001	699	685	23
									5-04-2001	675	--	--
									5-18-2001	676	--	--
									7-17-2001	682	--	--
									10-08-2001	692	--	--
Ac-UR007	302202	922151	--	I	40	--	--	--	5-15-2001	705	679	46
Ac-UR008	301629	922317	--	I	--	--	--	--	5-24-2001	690	--	--
									6-19-2001	689	--	--
									7-12-2001	673	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Calcasieu Parish												
Cu-168	300440	930845	11202LC	I	7.81	375	--	--	6-04-2001	514	508	38
Cu-171	300820	930837	11202LC	I	13	375	--	--	4-27-2000	466	--	--
									5-16-2000	466	--	--
									5-06-2001	480	--	--
									5-16-2001	491	--	--
									5-19-2001	481	--	--
									5-23-2001	497	--	--
									5-30-2001	497	--	--
									6-19-2001	491	--	--
									6-26-2001	498	--	--
Cu-633	300545	930652	11202LC	I	--	300	--	--	5-18-2000	732	--	--
									6-18-2000	754	--	--
									5-22-2001	746	733	49
Cu-688	300540	931303	11205LC	I	10.96	694	614	694	6-22-2000	550	--	--
Cu-771	301336	931830	11202LC	O	17.76	241	231	241	3-14-2000	420	415	16
									9-12-2000	425	425	16
									3-07-2001	409	421	15
									9-17-2001	424	419	15
									4-11-2002	425	416	16
									9-12-2002	430	415	16
									3-27-2003	429	416	16
Cu-787	300353	932102	11205LC	O	4.33	734	729	734	3-14-2000	543	528	49

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Calcasieu Parish—Continued												
Cu-787	300353	932102	11205LC	O	4.33	734			9-12-2000	537	527	50
									3-06-2001	514	532	48
									9-18-2001	527	520	47
									4-11-2002	525	510	46
									9-12-2002	523	509	45
									3-27-2003	523	507	45
Cu-812	301211	930133	112CHCTU	I	--	265	--	--	5-15-2000	993	--	--
									4-30-2003	1,010	998	130
Cu-960	301031	932049	11205LC	O	21	598	592	598	9-13-2000	774	753	140
									3-05-2001	759	750	140
									9-17-2001	755	744	140
									4-10-2002	758	729	140
									9-12-2002	754	722	130
									3-27-2003	766	733	140
Cu-1012	300707	930435	11202LC	I	20	363	280.2	363	5-17-2000	817	--	--
									6-20-2000	769	--	--
									4-29-2003	789	783	57
Cu-1092	300858	931131	11205LC	I	17.5	600	519.2	600.1	5-18-2000	488	--	--
Cu-1093	301341	930024	112CHCTU	I	25	303	243	303	4-24-2000	906	--	--
									5-20-2000	915	--	--
									6-16-2000	916	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Calcasieu Parish—Continued												
									9-03-2000	901	--	--
Cu-1093	301341	930024	112CHCTU	I	25	303			4-16-2001	900	--	--
									5-28-2001	891	--	--
									5-02-2002	933	--	--
Cu-1211	301753	930239	11202LC	I	20	205	143	205	5-16-2000	826	--	--
Cu-1253	301544	930455	11202LC	I	21	236	176	236	4-24-2000	1,220	--	--
									5-08-2000	1,230	--	--
									5-20-2000	1,180	--	--
									7-07-2000	1,180	--	--
									9-01-2000	1,190	--	--
									3-08-2001	1,200	--	--
									4-12-2001	1,190	--	--
									5-03-2001	1,140	--	--
									5-10-2001	1,070	--	--
									5-22-2001	1,230	1,220	260
									5-27-2001	1,180	--	--
									4-02-2002	1,230	--	--
									5-09-2002	1,220	--	--
									5-01-2003	1,200	--	--
Cu-1287	301223	930420	11202LC	I	20	282	200	282	5-07-2000	1,270	--	--
									5-18-2000	1,270	--	--
Cu-1369	301040	930823	11205LC	I	21	594	--	--	5-16-2000	504	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Calcasieu Parish—Continued												
									6-21-2000	512	--	--
Cu-1369	301040	930823	11205LC	I	21	594			5-15-2001	515	510	57
Cu-1385	301324	931705	11205LC	N	15	580	400	575	3-14-2000	805	784	140
									9-13-2000	754	734	130
									3-06-2001	715	712	120
									10-11-2001	699	673	110
									9-12-2002	699	671	110
									3-27-2003	694	663	110
Cu-1386	301048	930348	11202LC	I	24	325	204	316	4-06-2000	1,380	--	--
									5-09-2001	1,380	1,350	160
									6-05-2001	1,230	--	--
Cu-1387	301100	930305	11202LC	I	30	283	203	283	4-26-2000	1,350	--	--
									6-07-2000	1,330	--	--
									6-05-2001	1,210	--	--
									7-25-2001	1,160	--	--
Cu-1389	301123	930119	112CHCTU	I	24	302	182	302	5-22-2001	997	989	120
Cu-1391	301205	930157	11202LC	I	23	254	--	--	4-25-2000	1,080	--	--
									5-15-2000	1,090	--	--
Cu-1397	301307	930409	11202LC	I	22	291	181	291	4-26-2000	1,310	--	--
									6-07-2000	1,290	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Calcasieu Parish—Continued												
									5-22-2001	1,290	1,270	210
									6-05-2001	1,160	--	--
Cu-1398	300954	930535	11202LC	I	22	322	216	321	4-27-2000	1,060	--	--
Cu-1398	300954	930535	11202LC	I	22	322			5-16-2000	985	--	--
									4-23-2001	973	--	--
Cu-1402	301006	925948	112CHCTU	I	17	275	255	275	5-05-2000	1,690	--	--
									5-15-2000	1,100	--	--
									5-23-2000	1,360	--	--
									6-09-2000	1,020	--	--
Cu-1415	301353	930224	11202LC	I	16	273	167	272	4-25-2000	1,240	--	--
									5-15-2000	1,250	--	--
									5-23-2001	1,250	1,220	260
Cu-1422	301250	930320	11202LC	I	22	262	200	262	6-05-2002	1,120	1,180	200
Cu-1432	300930	930944	11202LC	I	19	272	202	272	6-12-2000	488	--	--
									5-22-2001	494	483	42
Cu-9069Z	300838	930318	11202LC	I	21	270	260	270	4-26-2000	714	--	--
									5-16-2000	897	--	--
									5-27-2000	713	--	--
									6-08-2000	912	--	--
									6-17-2000	907	--	--
									6-22-2000	913	--	--
									5-15-2001	900	895	74

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Calcasieu Parish—Continued												
Cu-UR001	300928	932941	--	I	15	--	--	--	5-17-2001	434	--	--
									5-18-2001	433	--	--
Cu-UR002	300815	932836	--	I	10	--	--	--	5-17-2001	506	--	--
Cu-UR002	300815	932836	--	I	10	--			5-18-2001	526	--	--
									5-19-2001	534	--	--
Cu-UR003	301225	925954	--	I	23	190	150	190	4-27-2000	1,090	--	--
									6-16-2000	1,130	--	--
									4-02-2001	1,700	--	--
									4-24-2001	2,020	--	--
									5-22-2001	1,930	--	--
									6-20-2001	2,010	--	--
									8-30-2001	2,140	--	--
									2-15-2002	2,750	--	--
									3-18-2002	2,440	--	--
									6-01-2002	2,150	--	--
									4-08-2003	2,860	--	--
Cu-UR004	301340	930133	--	I	23	--	--	--	4-25-2000	1,080	--	--
									5-15-2000	1,090	--	--
Cu-UR005	300536	930547	--	I	26	--	--	--	6-12-2000	825	--	--
									6-17-2000	801	--	--
Cu-UR006	300351	930648	--	I	16	--	--	--	4-28-2000	714	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
						Calcasieu Parish—Continued						
Cu-UR009	300830	930559	--	I	19	--	--	--	4-27-2000	982	--	--
									5-31-2000	988	--	--
Cu-UR010	301009	930241	--	I	20	--	--	--	7-11-2000	688	--	--
									7-18-2000	676	--	--
Cu-UR010	301009	930241	--	I	20	--			7-25-2000	674	--	--
Cu-UR015	300817	930250	--	I	--	--	--	--	5-16-2000	653	--	--
									6-21-2000	645	--	--
									5-15-2001	640	629	48
Cu-UR016	301347	925948	--	I	30	--	--	--	4-25-2000	614	--	--
									5-16-2000	611	--	--
									5-17-2000	617	--	--
Cu-UR019	300639	930502	--	I	--	--	--	--	5-16-2000	962	--	--
									6-20-2000	957	--	--
						Cameron Parish						
Cn-22	300042	930854	11202LC	I	10	388	--	--	1-30-2000	572	--	--
									4-27-2000	570	--	--
Cn-80L	295846	923811	112CHCTU	O	4.73	481	475	481	3-15-2000	1,290	1,260	250
									9-13-2000	1,210	1,180	270
									3-09-2001	1,300	1,250	260
									9-19-2001	1,300	1,260	260
									4-09-2002	1,300	1,260	260
									9-10-2002	1,280	1,240	250

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Cameron Parish—Continued												
									3-28-2003	1,320	1,270	260
Cn-90	295611	930448	11202LC	O	3.19	396	386	396	3-13-2000	998	960	160
									9-11-2000	985	962	170
									3-07-2001	964	973	170
Cn- 90	295611	930448	11202LC	O	3.19	396			9-18-2001	980	963	170
									4-10-2002	985	959	170
									9-11-2002	988	959	160
									3-26-2003	996	955	160
Cn-92	300104	930156	11202LC	O	5.5	443	438	443	3-13-2000	1,830	1,770	390
									9-12-2000	1,820	1,770	410
									3-07-2001	1,870	1,840	430
									9-18-2001	1,950	1,890	450
									4-10-2002	1,900	1,840	430
									9-11-2002	1,870	1,820	420
									3-26-2003	1,850	1,800	410
Cn-196	300122	930604	11202LC	I	10	420	320	420	4-20-2000	1,270	--	--
									5-11-2000	1,270	--	--
									5-25-2000	1,270	--	--
									6-03-2000	1,270	--	--
									6-15-2000	1,270	--	--
									4-29-2003	1,250	1,210	240

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
						Cameron Parish—Continued						
Cn-197	300216	930518	11202LC	I	10	462	362	462	4-27-2000	762	--	--
									6-14-2000	764	--	--
Cn-198	300029	930716	11202LC	I	10	402	302	402	4-20-2000	1,190	--	--
									5-11-2000	1,190	--	--
									5-25-2000	1,190	--	--
Cn-198	300029	930716	11202LC	I	10	402			6-03-2000	1,190	--	--
									6-16-2000	1,200	--	--
									6-21-2000	1,180	--	--
									6-29-2000	1,160	--	--
									7-19-2000	1,190	--	--
Cn-UR001	300001	930859	--	I	10	--	--	--	4-27-2000	622	--	--
									5-31-2000	622	--	--
Cn-UR002	300150	930718	--	I	20	--	--	--	4-27-2000	853	--	--
									5-31-2000	861	--	--
						Evangeline Parish						
Ev-673	303801	922500	112CHCT	P	60	247	187	247	5-16-2001	740	720	68
Ev-834	303617	923013	112CHCT	I	50	260	190	260	5-15-2001	336	321	27
Ev-879	304545	921911	112CHCT	I	80	220	153	220	5-16-2001	341	323	12
Ev-889	303944	922725	112CHCT	I	60	201	151	201	5-15-2001	599	580	66
Ev-923	304201	922636	112CHCT	I	--	188	--	--	5-16-2001	793	751	110
Ev-UR001	303832	922637	--	I	--	--	--	--	5-15-2001	737	712	83
Ev-UR003	303832	922744	--	I	--	--	--	--	5-15-2001	488	471	24

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
						Evangeline Parish—Continued						
Ev-UR004	304036	922343	--	I	--	--	--	--	5-16-2001	479	458	32
Ev-UR005	303704	921717	--	I	--	--	--	--	5-16-2001	689	648	28
Ev-UR006	304254	922021	--	I	--	--	--	--	5-17-2001	648	621	60
Ev-UR007	304346	922015	--	I	--	--	--	--	5-17-2001	546	526	57
Ev-UR009	303222	922206	--	I	58	--	--	--	4-07-2001	606	--	--
Ev-UR009	303222	922206	--	I	58	--			4-17-2001	603	--	--
									4-23-2001	604	--	--
						Iberia Parish						
I-93	300035	914433	112CHCTU	O	18.53	585	580	585	3-16-2000	734	713	43
									9-15-2000	740	714	42
									3-08-2001	728	711	40
									9-13-2001	716	702	39
									3-27-2002	729	701	39
									9-10-2002	728	689	37
									3-25-2003	730	691	38
						Jefferson Davis Parish						
JD-50	301244	924435	112CHCTU	I	--	310	--	--	6-06-2000	455	--	--
									7-07-2000	450	--	--
JD-79	300404	924429	112CHCTU	I	18.77	313	--	--	6-18-2001	588	--	--
									6-20-2001	585	--	--
JD-135	301439	924637	112CHCTU	I	20	--	--	--	5-17-2000	449	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Jefferson Davis Parish—Continued												
									6-08-2000	450	--	--
									5-03-2001	454	442	48
									3-06-2002	467	--	--
									6-10-2002	452	--	--
JD-176	301536	924405	112CHCTU	I	--	290	--	--	4-24-2000	888	--	--
									7-31-2000	857	--	--
JD-176	301536	924405	112CHCTU	I	--	290			8-10-2000	858	--	--
									9-04-2000	849	--	--
									10-02-2000	857	--	--
									3-02-2001	874	--	--
									4-02-2001	867	--	--
									5-08-2001	848	--	--
									7-05-2001	846	--	--
									8-25-2001	862	--	--
JD-241	301913	925848	112CHCTU	I	25	275	195	275	4-22-2001	554	--	--
JD-352	302314	925713	112CHCT	I	30	329	--	--	4-21-2000	259	--	--
									5-30-2000	259	--	--
JD-447	302050	925645	112CHCT	I	--	262	--	--	3-06-2001	318	--	--
									4-05-2001	317	--	--
									5-07-2001	321	--	--
									5-25-2001	320	--	--
									7-22-2001	325	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Jefferson Davis Parish—Continued												
									4-22-2002	344	--	--
									5-06-2002	339	--	--
									5-14-2002	341	--	--
									6-05-2002	336	--	--
									3-04-2003	337	--	--
JD-469	300845	924313	112CHCTU	I	15	276	196	276	2-25-2001	615	--	--
JD-469	300845	924313	112CHCTU	I	15	276			4-06-2001	613	--	--
									5-22-2001	614	--	--
									6-30-2001	616	--	--
									8-24-2001	623	--	--
JD-491	300508	924056	112CHCTU	P	10	377	326	377	3-15-2000	701	693	99
									9-13-2000	713	696	100
									3-09-2001	705	696	99
									9-19-2001	712	695	98
									4-09-2002	711	690	99
									9-13-2002	712	680	96
									3-28-2003	717	692	98
JD-493	302509	925321	112CHCT	I	37.95	220	160	220	5-25-2001	245	--	--
									6-06-2002	245	226	22
JD-499	301752	924009	112CHCTU	I	30	250	190	250	5-16-2001	448	438	49
JD-523	301550	924514	112CHCTU	I	25	311	229.58	311	4-24-2000	466	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Jefferson Davis Parish—Continued												
JD-650	301350	924411	112CHCTU	I	22	263	183	263	4-24-2000	437	--	--
JD-727	300552	924559	112CHCTU	I	15	327.5	247.04	327.5	5-02-2001	530	--	--
									5-24-2001	526	--	--
JD-751	300547	924426	112CHCTU	I	10	193	133	193	5-03-2001	606	604	68
									6-07-2002	578	596	66
JD-772	301354	924455	112CHCTU	I	27	340	259	340	5-16-2001	465	456	50
									6-07-2002	449	453	49
JD-817	301352	925614	112CHCTU	I	20	296	227	296	5-24-2000	779	--	--
									6-26-2000	982	--	--
									2-20-2001	959	--	--
									4-16-2001	982	--	--
JD-860	301242	925920	112CHCTU	I	26	275	215	275	4-27-2000	1,290	--	--
									5-16-2000	1,290	--	--
									4-02-2001	1,050	--	--
									4-24-2001	1,060	--	--
									5-22-2001	1,090	--	--
									6-20-2001	1,070	--	--
									8-30-2001	1,060	--	--
									2-15-2002	1,090	--	--
									3-18-2002	1,170	--	--
									6-01-2002	1,070	--	--
									4-08-2003	1,060	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Jefferson Davis Parish—Continued												
									4-29-2003	1,120	1,100	160
JD-867	301126	924801	112CHCTU	I	16	202	142	202	6-06-2000	451	--	--
									7-13-2000	422	--	--
JD-871	300604	924850	112CHCTU	I	9	200	140	200	5-18-2000	540	--	--
									6-09-2000	542	--	--
									5-03-2001	538	536	57
JD-UR002	300616	924631	--	I	20	--	--	--	5-18-2000	632	--	--
JD-UR002	300616	924631	--	I	20	--			5-24-2000	631	--	--
									6-13-2000	618	--	--
									7-18-2000	616	--	--
									7-31-2000	616	--	--
									8-15-2000	620	--	--
									4-11-2001	604	--	--
									5-03-2001	610	611	68
JD-UR006	301203	925715	--	I	16	--	--	--	9-12-2000	1,030	--	--
									10-19-2001	1,030	--	--
									9-15-2002	1,080	--	--
JD-UR008	301701	925903	--	I	33	--	--	--	2-22-2001	1,140	--	--
									4-08-2001	1,120	--	--
JD-UR009	301724	930111	--	I	26	--	--	--	4-21-2000	959	--	--
									5-30-2000	969	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
						Jefferson Davis Parish—Continued						
JD-UR011	301000	924807	--	I	13	--	--	--	6-06-2000	456	--	--
JD-UR012	301222	924747	--	I	16	--	--	--	6-06-2000	398	--	--
									7-17-2000	391	--	--
JD-UR013	301159	924630	--	I	20	--	--	--	6-06-2000	456	--	--
									7-07-2000	447	--	--
JD-UR014	301852	925724	--	I	--	--	--	--	4-06-2001	514	--	--
									4-15-2001	571	--	--
									4-27-2001	516	--	--
JD-UR014	301852	925724	--	I	--	--			5-11-2001	516	--	--
									5-26-2001	622	--	--
									4-29-2002	653	--	--
									5-11-2002	663	--	--
									5-15-2002	626	--	--
									6-17-2002	565	--	--
									8-11-2002	589	--	--
JD-UR015	301700	925903	--	I	33	--	--	--	5-14-2000	1,310	--	--
									5-30-2000	1,300	--	--
JD-UR017	300409	925222	--	I	7	--	--	--	5-02-2001	536	--	--
									5-24-2001	550	--	--
JD-UR018	301725	930111	--	I	26	--	--	--	5-19-2000	969	--	--
									5-03-2001	957	945	180
JD-UR019	301747	930020	--	I	33	--	--	--	5-19-2000	918	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Jefferson Davis Parish—Continued												
									5-03-2001	812	797	150
JD-UR020	301708	930048	--	I	33	--	--	--	5-19-2000	828	--	--
JD-UR022	301836	925648	--	I	--	--	--	--	5-14-2001	435	--	--
									5-26-2001	447	--	--
									8-11-2002	472	--	--
									4-29-2002	480	--	--
									5-11-2002	481	--	--
									5-25-2002	465	--	--
Lafayette Parish												
Lf-524	300605	915935	112CHCTU	P	25	174	141	174	3-15-2000	325	327	6.8
									9-14-2000	295	289	7.8
									3-08-2001	282	309	7.1
									9-14-2001	320	326	7.3
									4-09-2002	310	301	7.8
									9-10-2002	307	299	8.4
St. Landry Parish												
SL-142	302732	921029	112CHCT	I	50	235	--	--	5-03-2002	--	497	23
SL-331	303200	921005	112CHCT	I	62	--	--	--	4-03-2002	--	541	16
SL-345	304911	920637	112ACFL	I	40	158	90	157.5	4-30-2003	1,220	1,200	100
SL-459	303151	922145	112CHCT	I	51	249	179	249	4-07-2001	609	--	--
									4-17-2001	606	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
St. Landry Parish—Continued												
									4-23-2001	599	--	--
									6-07-2002	613	590	42
SL-564	304845	921149	112ACFL	I	43	199	123	199	5-04-2001	806	--	--
SL-673	304832	921142	112ACFL	I	48	187	123	186	5-04-2001	773	--	--
SL-714	304827	921011	112CHCT	I	45	178	126	176	2-24-2001	1,100	--	--
									5-30-2001	1,070	--	--
									7-30-2001	1,080	--	--
									4-30-2003	1,110	1,110	95
SL-UR001	304920	921210	--	I	46	--	--	--	4-20-2001	791	--	--
									11-09-2001	514	--	--
SL-UR001	304920	921210	--	I	46	--			2-01-2002	--	597	18
SL-UR004	304416	920343	--	I	40	--	--	--	1-22-2001	1,800	--	--
									2-26-2001	1,710	--	--
									4-05-2001	1,810	--	--
									5-04-2001	1,810	--	--
									7-27-2001	1,800	--	--
SL-UR005	304555	915248	--	I	39	--	--	--	4-26-2001	657	--	--
SL-UR006	304807	915239	--	I	39	--	--	--	4-26-2001	910	--	--
									5-31-2001	821	--	--
SL-UR007	303459	920852	--	I	66	--	--	--	5-03-2002	--	526	15
St. Martin Parish												
SMn-109	301304	914240	112CHCTU	O	11.34	375	370	375	3-16-2000	1,200	1,130	110

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
St. Martin Parish—Continued												
									9-14-2000	1,190	1,150	120
									3-08-2001	1,180	1,150	110
									9-13-2001	1,170	1,150	120
									3-27-2002	1,190	1,150	120
									9-09-2002	1,190	1,150	120
									3-25-2003	1,200	1,150	120
St. Mary Parish												
SM-57U	294749	914023	112CHCTU	O	8.72	638	628	638	3-16-2000	1,140	1,120	180
									9-15-2000	1,170	1,130	190
									3-08-2001	1,150	1,120	180
SM-57U	294749	914023	112CHCTU	O	8.72	638			9-13-2001	1,140	1,120	190
									3-28-2002	1,160	1,120	190
									9-10-2002	1,170	1,130	180
									3-25-2003	1,180	--	--
Vermilion Parish												
Ve-170	300121	920057	112CHCTS	H	--	70	50	70	8-03-2000	300	277	4.2
Ve-312	300236	923910	112CHCTU	I	6	205	155	205	5-17-2001	703	--	--
									6-18-2001	709	--	--
Ve-384	300257	924011	112CHCTU	I	6	348	--	--	5-17-2001	630	--	--
									6-18-2001	645	--	--
Ve-425	295927	922755	112CHCTU	I	--	--	--	--	6-05-2000	831	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
						Vermilion Parish—Continued						
Ve-426	300000	922722	112CHCTU	I	--	354	--	--	6-12-2000	912	--	--
									6-13-2000	918	--	--
									6-15-2000	920	--	--
									8-28-2000	887	--	--
									8-29-2000	900	--	--
									5-30-2001	878	--	--
									5-31-2001	877	--	--
Ve-432	295835	922549	112CHCTU	I	--	350	--	--	4-26-2002	821	745	54
Ve-460	921655	295645	112CHCTU	I	9.78	300	--	--	5-05-2000	1,300	--	--
Ve-586	300240	920832	112CHCT	I	15.4	259	195	259	4-24-2002	618	595	30
Ve-637L	295345	921007	112CHCTU	O	4.06	243	233	243	3-16-2000	2,790	2,650	680
Ve-637L	295345	921007	112CHCTU	O	4.06	243			9-11-2000	2,750	2,700	690
									3-08-2001	2,750	2,680	700
									9-14-2001	2,760	2,710	690
									3-28-2002	2,800	2,740	720
									9-10-2002	2,860	2,750	700
									3-26-2003	2,890	2,770	730
Ve-639	293845	922649	112CHCTU	O	5.84	608	603	608	3-13-2000	1,550	1,500	280
									9-11-2000	1,550	1,510	300
									3-07-2001	1,510	1,500	290
									9-14-2001	1,520	1,500	300
									3-28-2002	1,540	1,540	300

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Vermilion Parish—Continued												
									9-10-2002	1,550	1,500	300
									3-26-2003	1,560	1,500	300
Ve-725	300315	921909	112CHCTU	I	14	300	--	--	4-24-2002	1,010	945	110
Ve-733	300537	921801	112CHCTU	I	15	297	190.67	297.33	4-24-2002	--	749	69
Ve-1081	295947	922310	112CHCTU	I	10	190	160	190	4-26-2002	726	688	37
Ve-1123	300351	923108	112CHCTU	I	10	175	--	--	5-16-2001	--	721	42
Ve-1152	300501	921534	112CHCTU	I	10	235	195	235	4-24-2002	--	548	18
Ve-UR001	295951	922913	--	I	6	--	--	--	6-13-2000	589	--	--
									8-18-2000	601	--	--
									9-19-2000	593	--	--
									5-10-2001	823	802	46
Ve-UR002	300039	923232	--	H	--	--	--	--	5-09-2000	883	--	--
									6-06-2000	882	--	--
									4-01-2001	856	--	--
									5-02-2001	881	--	--
									5-10-2001	894	875	66
									5-29-2001	862	--	--
									7-02-2001	887	--	--
Ve-UR003	300129	921243	--	I	23	--	--	--	6-03-2000	794	--	--
									6-17-2000	772	--	--
									7-03-2000	755	--	--

Table 3. Selected data for wells in the Chicot aquifer system or the Atchafalaya aquifer in southwestern Louisiana, including specific conductance values and chloride concentrations, 2000-03.—Continued

[NAD 27, North American Datum of 1927; NGVD 29, National Geodetic Vertical Datum of 1929; aquifer code: 112ACFL, Atchafalaya aquifer; 112CHCT, massive sand; 112CHCTU, upper sand; 112CHCTS, shallow sand; 11202LC, "200-foot" sand; and 11205LC, "500-foot" sand. Primary use of well: H, domestic; I, irrigation; N, industry; O, observation; and P, public supply. --, no data]

Well number	Latitude (NAD 27)	Longitude (NAD 27)	Aquifer code	Primary use of well	Altitude of land surface (feet relative to NGVD 29)	Depth of well (feet)	Depth to top of screen (feet)	Depth to bottom of screen (feet)	Date sampled	Field specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Laboratory specific conductance (microsiemens per centimeter at 25 degrees Celsius)	Chloride concentration (milligrams per liter)
Vermilion Parish—Continued												
									7-15-2000	752	--	--
									8-15-2000	717	--	--
Ve-UR004	300246	921344	--	I	26	--	--	--	6-07-2000	681	--	--
									6-20-2000	687	--	--
									7-07-2000	669	--	--
									8-14-2000	666	--	--
Ve-UR005	295705	921601	--	I	13	--	--	--	6-14-2000	865	--	--
									6-28-2000	838	--	--
									7-15-2000	842	--	--
									7-28-2000	833	--	--
									8-14-2000	835	--	--
Ve-UR007	300239	924019	--	I	6	--	--	--	5-17-2001	654	--	--
Ve-UR007	300239	924019	--	I	6	--			6-18-2001	660	--	--
Ve-UR010	300524	920734	--	I	26	--	--	--	5-10-2001	595	584	27
Ve-UR011	300233	922650	--	I	10	--	--	--	4-26-2002	957	872	99
Ve-UR012	295644	921026	--	I	16	--	--	--	5-08-2002	--	932	180

NYMAN, D.J., HALFORD, K.J., AND MARTIN, A.M., 1990

GEOHYDROLOGY AND SIMULATION FLOW IN THE CHICOT AQUIFER SYSTEM

OF SOUTHWESTERN LOUISIANA

STATE OF LOUISIANA
DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

WATER RESOURCES
TECHNICAL REPORT
No. 50

GEOHYDROLOGY AND SIMULATION OF FLOW IN THE CHICOT AQUIFER SYSTEM OF SOUTHWESTERN LOUISIANA

Prepared by
DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY
In cooperation with
LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

1990

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U.S. GEOLOGICAL SURVEY

Published by the

LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

Baton Rouge, Louisiana

1990

STATE OF LOUISIANA

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
mile (mi)	1.609	kilometer (km)
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
billion gallons per day (Bgal/d)	43.81	cubic meter per second (m^3/s)

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows: °F = 1.8 X °C + 32.

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Sea Level Datum of 1929."

The use of product names in this report is for identification purposes only and does not constitute endorsement of products by the U.S. Geological Survey or the Louisiana Department of Transportation and Development.

GEOHYDROLOGY AND SIMULATION OF FLOW IN THE CHICOT AQUIFER SYSTEM OF SOUTHWESTERN LOUISIANA

By

Dale J. Nyman, Keith J. Halford, and Angel Martin, Jr.

ABSTRACT

Water was pumped at about 1 billion gallons per day from the Chicot aquifer system in 1980 by industry and rice growers in southwestern Louisiana. Records indicate that water levels in wells declined, on average, as much as 1 foot per year from 1900 to 1981 in the Lake Charles and rice-growing areas. Water levels rose, on average, 2 feet per year during the period 1982-85 because pumping rates during the period were reduced by 38 percent to 616 million gallons per day.

The Chicot aquifer system consists of a complex series of alternating beds of unconsolidated sand, gravel, silt, and clay. Under predevelopment conditions, ground-water flow was primarily from recharge areas where the aquifers outcrop in southern Vernon and Rapides Parishes and in northern Beauregard, Allen, and Evangeline Parishes to discharge areas southward along the coast and eastward in the Atchafalaya River basin. As a result of development, flow throughout the aquifer system now converges to pumping centers in the rice-growing area and the Lake Charles area.

A digital ground-water flow model was developed to simulate flow in the Chicot aquifer system and to estimate the effects of pumping. In general, model-computed water levels compare closely with observed levels. Model results indicate that: (1) flow patterns in the Chicot aquifer system have been significantly altered downgradient from the area of outcrop since predevelopment; (2) approximately a fourfold increase (from 259 to 1,113 million gallons per day) in flow through the system has occurred since major development began; (3) water levels in and near the pumping centers declined, on average, 1 foot per year from predevelopment to 1981; (4) under 1981 conditions, vertical leakage was the largest component of recharge; and (5) water derived from aquifer storage is a relatively small part of flow in the entire system.

The model is least sensitive to changes in aquifer storage and most sensitive to changes in the vertical conductance of the confining units. Simulations indicate that, disregarding the possibility of saltwater encroachment in the aquifers along the coast, pumping rates 50 to 100 percent larger than the 1980 rate can be maintained indefinitely with the available recharge.

INTRODUCTION

The effects of the development of ground-water resources on the ground-water flow system in southwestern Louisiana paralleled the expansion of acreage devoted to the planting of rice. Rice was introduced into southwestern Louisiana during the 1800's. Initially, rice fields were irrigated using surface-water supplies such as streams, elevated canals, and tidal flow in the coastal marshes. Although irrigation wells were used at the turn of the century, they did not become widespread until after the "Great Depression" of the 1930's. Pumpage for industrial and municipal uses also began to increase rapidly in the late 1930's.

The average pumping rate from the Chicot aquifer system in Louisiana during 1980 was about 1 Bgal/d, which included about 850 Mgal/d for rice irrigation (Walter, 1982). Pumpage had declined by 38 percent to 616 Mgal/d by 1985 (Lurry, 1987, table 2) as a result of reduced pumpage for rice production and industrial use, and water levels rose, on average, 2 ft/yr from 1982 to 1985.

Today (1988) the Chicot aquifer system is the principle source of ground water for southwestern Louisiana and is the most heavily pumped aquifer system in the State. The present and future effects of pumpage on the aquifer system are of concern to State and local water-resources managers.

During the fall of 1984, the U.S. Geological Survey, in cooperation with the Louisiana Department of Transportation and Development, began a study to develop an understanding of the geohydrology of the Chicot aquifer system in southwestern Louisiana and to estimate the effects of pumping stress on the system.

Purpose and Scope

This report describes the geohydrologic setting of the Chicot aquifer system and the flow of water through the system, and provides estimates of the present and future effects of pumpage on the aquifer system. Previous studies of the Chicot aquifer system in Louisiana and Texas were used to establish the broad geologic and hydrologic framework of the study area. A digital flow model was used to simulate flow in the aquifer system under predevelopment and 1981 conditions and to estimate the effects of pumpage. Although southwestern Louisiana is the area of primary interest, the continuity of the ground-water flow system into Texas required that an area in southeastern Texas be included in some aspects of the investigation.

Description of Study Area

The study area (fig. 1) has been divided into four generalized regions for identification purposes in this report. These regions are: the Lake Charles area, the rice-growing area, the outcrop area, and the Atchafalaya River basin. Most of the study area consists of low-lying flatland at

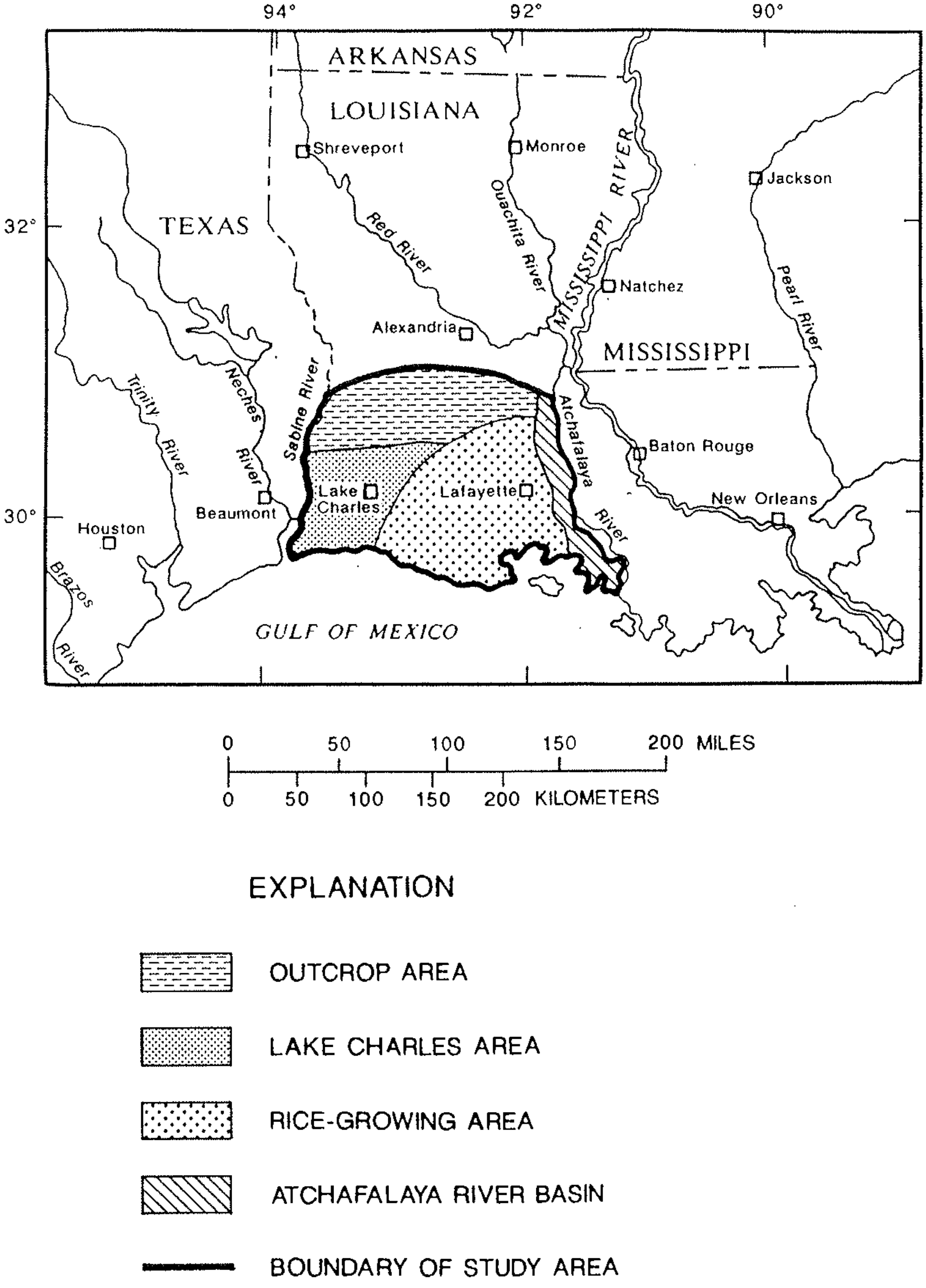


Figure 1.--Location of study area.

altitudes of less than 50 ft above sea level, but altitudes of 250 to 300 ft above sea level occur in the outcrop area.

Most of the study area is rural and used for growing rice. The proportion of land under cultivation decreases toward the coast because marshland extends from 30 to 50 mi inland from the shoreline. Lake Charles and Lafayette are the two largest cities within the study area. The Lake Charles industrial area lies within the Lake Charles area and covers about 60 mi^2 southwest of the city. Lake Charles supports a large petrochemical industry and commerce, whereas Lafayette is primarily a commercial center.

Climate of the region is warm and temperate with high humidity and frequent rains. The average annual temperature is 20 °C (U.S. Department of Commerce, 1984, p. 11). Temperatures range from highs of 38 °C in July and August to lows of -7 °C in December and January. The average annual rainfall is 59 in. and is relatively uniform from year to year (Jones and others, 1954, p. 15; Moody and others, 1986, p. 253). The region is primarily drained by the Sabine, Calcasieu, Vermilion, Mermentau, and Atchafalaya Rivers.

GEOHYDROLOGY

Geology

The Chicot aquifer system consists of a complex series of alternating beds of unconsolidated sand, gravel, silt, and clay. These beds are the result of two depositional environments. Sediments in the eastern part of the study area (the rice-growing area and the Atchafalaya River basin shown in fig. 1) were deposited by the ancestral Mississippi River that derived sediment and flow from the central part of the North American Continent. The sediments deposited in this environment are characterized by massive beds of coarse sand and gravel separated by relatively thin beds of clay (fig. 2).

Deposits in the western part of the study area (the Lake Charles area shown in fig. 1) were formed by rivers, such as the Calcasieu and Sabine, with smaller drainage areas and flow rates than the ancestral Mississippi River. The deposits formed by these rivers consist of thinner, finer grained beds of sand separated by relatively thick clays (figs. 3 and 4). Nyman (1984) describes the geohydrologic framework of the Chicot aquifer system within the study area in greater detail than presented in this report.

The Chicot aquifer system crops out in Louisiana in southern Vernon and Rapides Parishes and in northern Beauregard, Allen, and Evangeline Parishes (fig. 5). The aquifer system thickens and dips to the south at a rate of about 30 ft/mi. Along the southern edge of the outcrop area water in the aquifer system becomes confined beneath surface clay that thickens to as much as 200 ft downdip. Clay within the aquifer system in the outcrop area generally is thin and discontinuous. Within parts of the outcrop and downgradient areas, the Chicot aquifer system consists of a single relatively massive sand.

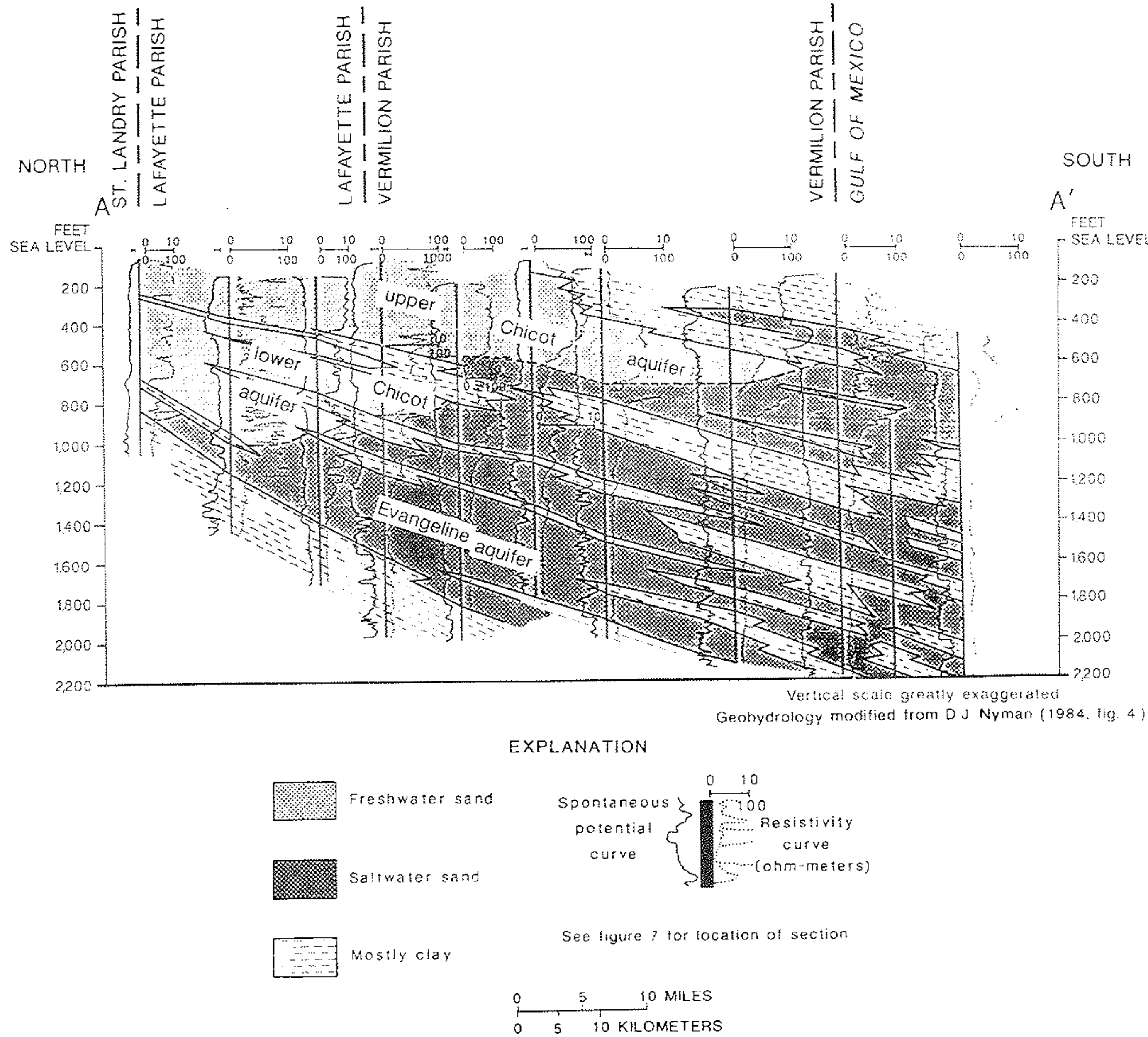


Figure 2.--Geohydrologic section in southwestern Louisiana, A-A'.

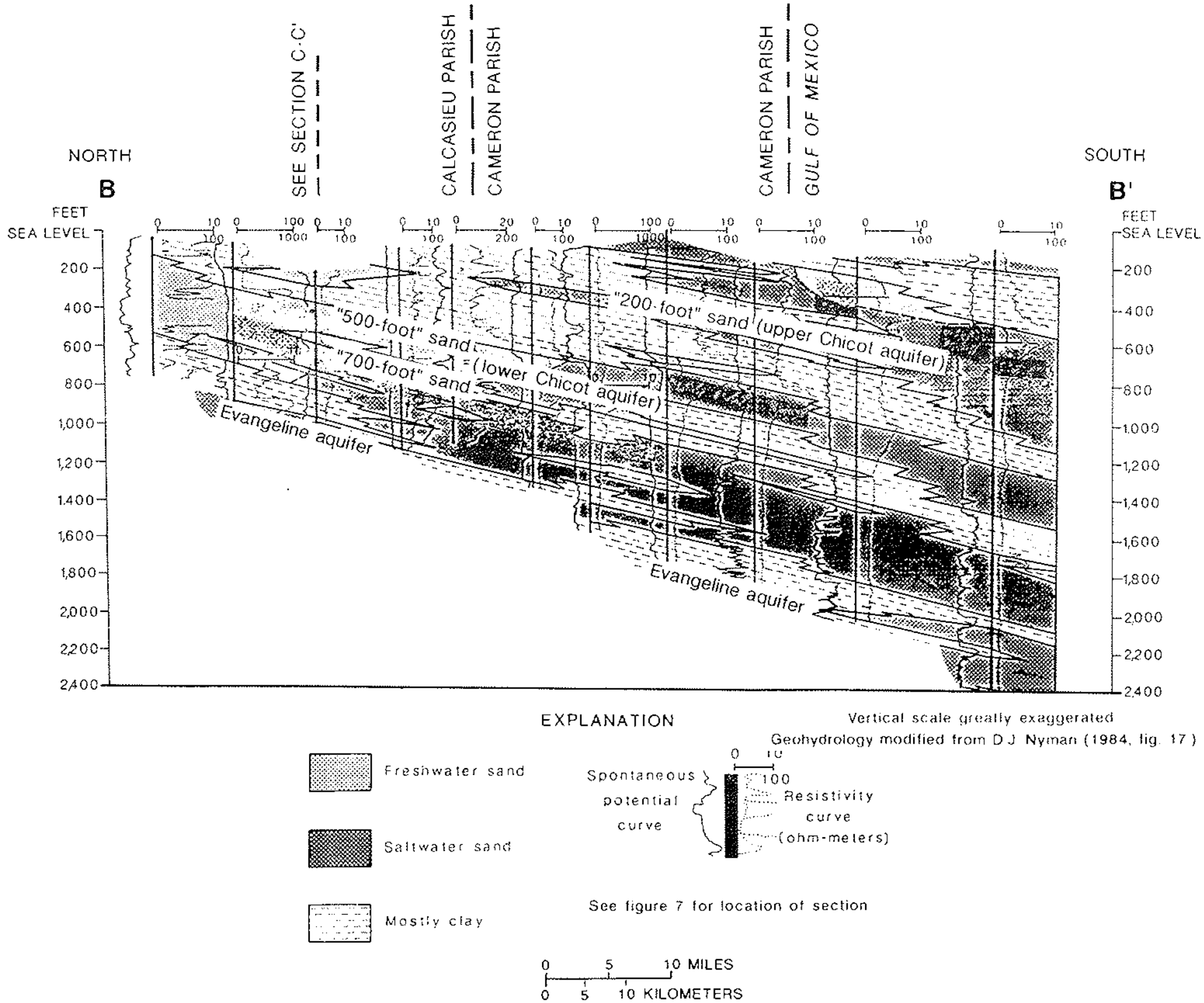


Figure 3.--Geohydrologic section in southwestern Louisiana, B-B'.

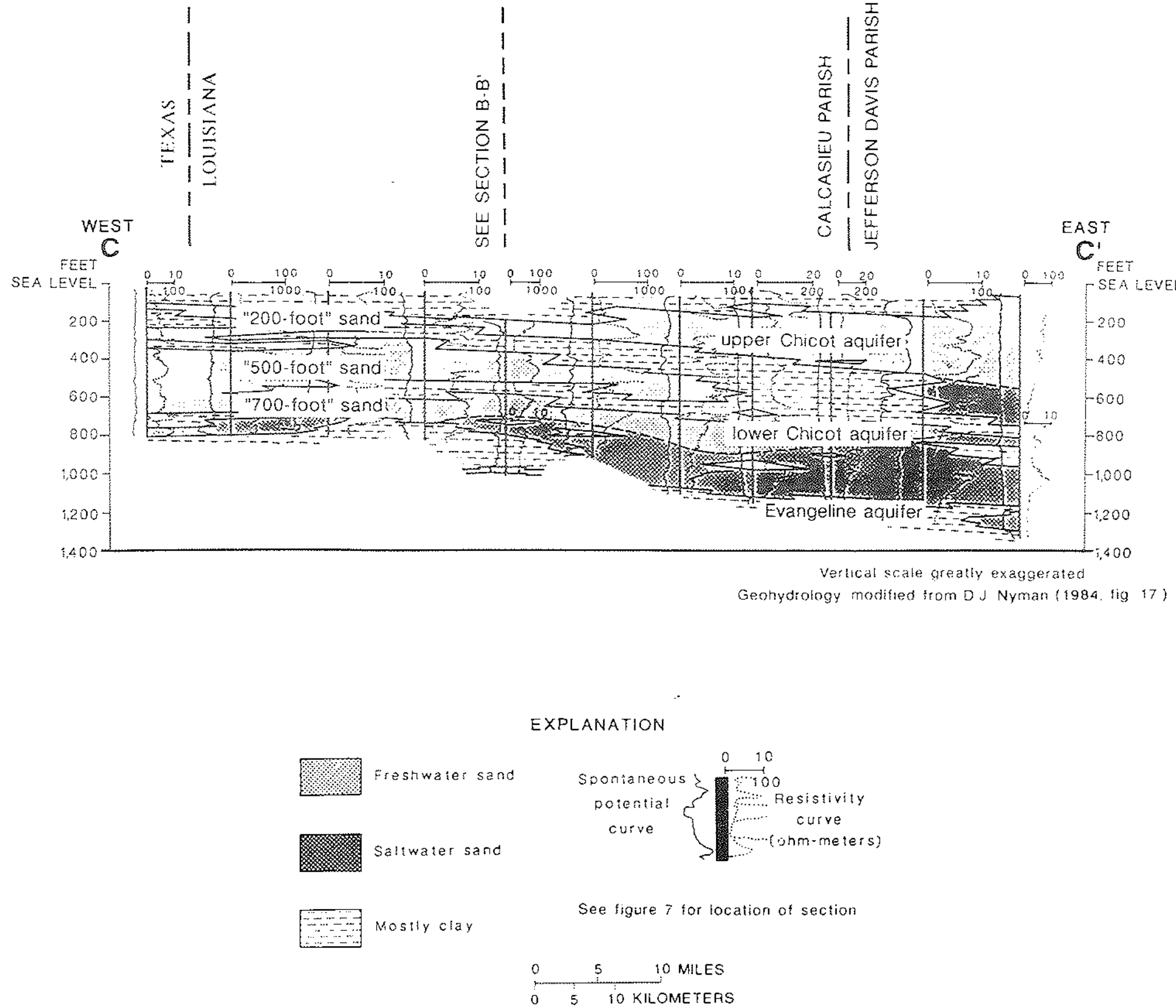
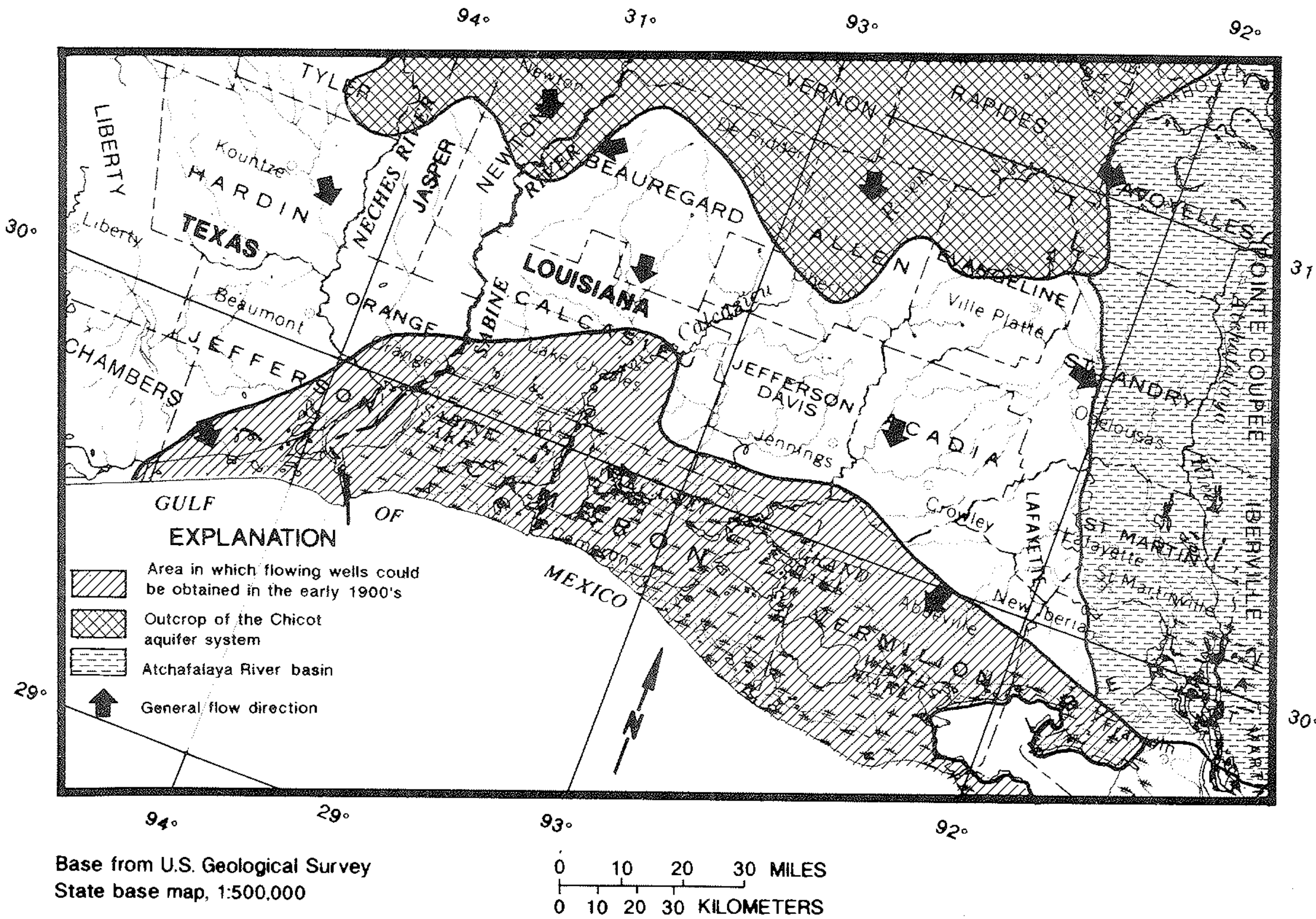


Figure 4.--Geohydrologic section in southwestern Louisiana, C-C'.



Base from U.S. Geological Survey
State base map, 1:500,000

Figure 5.--Generalized predevelopment flow paths of water in the Chicot aquifer system.

The range of thickness for the Chicot aquifer system within the study area is given in table 2. The southern limit of freshwater in the upper Chicot aquifer occurs near the coastline. This study includes that part of the Chicot aquifer system that contains water with dissolved-solids concentration up to 10,000 mg/L (milligrams per liter).

The lower Chicot aquifer is hydrologically similar to the upper Chicot aquifer, but the entire thickness of the lower Chicot aquifer contains saltwater south of the Calcasieu-Cameron Parish line. Nyman (1984) describes in detail the occurrence of saltwater in the Chicot aquifer system and presents illustrations showing the areal and vertical extent of freshwater in individual aquifers.

Previous investigators have divided the Chicot aquifer system in different ways. Table 1 shows the correlation between the aquifers and geologic units described in previous reports and the subdivisions currently used by the U.S. Geological Survey (Darwin Knochenmus, U.S. Geological Survey, written commun., 1988) which are used in this report. The Chicot aquifer system is divided into two aquifer units, the upper and lower Chicot aquifers. Further descriptions of these aquifers and their relation to units described by other investigators are given below.

In the rice-growing area and the Atchafalaya River basin (fig. 1) Harder and others (1967, p. 23) divided the Chicot aquifer system into two major units, the "upper sand unit" (upper Chicot aquifer in this report) and an undifferentiated lower unit (lower Chicot aquifer in this report). The upper Chicot aquifer contains mostly coarse sand grading to gravel near the base of individual beds. The sand beds generally are several hundred feet thick and are separated in places by thick discontinuous clays (figs. 2 and 4).

Jones (1950) divided the Chicot aquifer system in the Lake Charles industrial area into three major aquifers: the "200-foot" sand, "500-foot" sand, and "700-foot" sand. The names were based on the average depths of wells completed in these aquifers. The "200-foot" sand is considered part of the upper Chicot aquifer in this report, whereas the "500-foot" and "700-foot" sands are considered part of the lower Chicot aquifer.

The "500-foot" sand is the most important of the aquifers in the Lake Charles industrial area because it yields most of the water for the petrochemical industry and public supply. The "500-foot" sand ranges from 170 to 200 ft in thickness in the industrial area (Harder, 1960, p. 30). The aquifer is composed of fine sand at the top, grading to coarse sand and gravel near the base. The transition from freshwater to saltwater occurs in Cameron Parish near the Calcasieu-Cameron Parish line.

The "700-foot" sand contains saltwater in the southern two-thirds of Calcasieu Parish and is used less than the "500-foot" sand. The "700-foot" sand is pumped only in the northern part of the industrial area because saltwater occurs higher in the aquifer to the south and because of the risk of saltwater upconing to large-capacity wells. Lithology of the "700-foot" sand ranges from fine sand at the top to coarse sand at the bottom (Harder, 1960, p. 34). In the Lake Charles industrial area the aquifer is about 220 ft

Table 1.--Correlations between geohydrologic units and model layers used in this report and geologic and geohydrologic units described by previous investigators

System	Series	Wesselman (1971) south-eastern Texas	Jones (1950)[a]	Harder (1960)[b] Forma-tion	Harder (1960)[b] Hydro-logic unit	Harder and others (1967)[c]	Nyman (1984) Lake Charles industrial area	Nyman (1984) East of Lake Charles	This report Geo-hydrologic unit	This report Model layer
Quaternary	Holocene						Chicot aquifer system: Alluvium	Alluvium, Atchafalaya aquifer, and Abbeville unit	Chicot aquifer system: Upper Chicot aquifer	2
	Pleistocene			Prairie	Chicot shallow	Shallow sand				
		Upper aquifer	"200-foot" sand	Montgomery	"200-foot" sand	"Upper sand unit"	"200-foot" sand	"Upper sand"		
		Lower aquifer	"500-foot" sand	Bentley	"500-foot" sand	Undifferentiated	"500-foot" sand	Undifferentiated "lower sand"	Lower Chicot aquifer	3
			"700-foot" sand	Williana	"700-foot" sand		"700-foot" sand			4
Tertiary	Pliocene and Miocene	Evangeline aquifer		Foley	Evangeline aquifer	Evangeline aquifer	Evangeline aquifer	Evangeline aquifer	Evangeline aquifer	5 (base of model)
	Miocene	Burkeville aquiclude		Fleming			Jasper aquifer			
		Jasper aquifer								

[a] Lake Charles industrial area.
[b] For Lake Charles area.
[c] For area east of Lake Charles (rice-growing area and Atchafalaya River basin).

thick. The Chicot aquifer system in Texas (adjoining the study area) is described by Wesselman (1967; 1971). Aquifer conditions there are similar to those in the Lake Charles area.

The upper Chicot aquifer is as much as 200 ft thick in parts of the study area but generally is less than 100 ft thick. According to Harder (1960, p. 27), this aquifer in Calcasieu Parish grades from a fine or medium sand at the top to coarse sand, often with gravel, at the base. The aquifer is discontinuous, varying greatly in thickness and texture. Saltwater occurs in the lower part of the upper Chicot aquifer near the Calcasieu-Cameron Parish line from Calcasieu Lake (fig. 3) westward into Texas and eastward to St. Martin Parish, Louisiana.

The Evangeline aquifer underlies the Chicot aquifer system throughout the study area. The Evangeline aquifer is included in this study because it is a source of water for the Chicot aquifer system. The Evangeline aquifer ranges from 400 to 900 ft in thickness beneath the study area and contains an alternating sequence of relatively thin sand and thick clay beds. Individual sand beds are thinner and finer grained than those of the Chicot aquifer system (Whitfield, 1975, p. 15; Turcan and others, 1966, p. D235). Sand in the Evangeline aquifer ranges from fine to coarse. The Evangeline aquifer contains freshwater in the northern third of the study area.

Clays that confine the Chicot aquifer system thicken consistently from the outcrop to the coastline and range from 1 to 200 ft in thickness. Clays between and within the aquifer units generally are thin from west to east, and clays are thin and discontinuous between Lake Charles and the Atchafalaya River. The clay beds consist primarily of mixed layer clay and smectites, but silt-sized quartz is commonly an important constituent.

Water Quality

Freshwater in the Chicot aquifer system is predominantly a calcium-bicarbonate type (Nyman, 1989). Fresh ground water generally is suitable for irrigation and industrial use, but locally high iron concentrations (greater than 0.3 mg/L) may require treatment for public supply (Moody and others, 1986, p. 276). Based on analyses of 653 samples of water from the Chicot aquifers throughout the study area, hardness ranges from 3 to 750 mg/L and averages about 130 mg/L (D.J. Tomaszewski, U.S. Geological Survey, written commun., 1989).

Ground-Water Flow System

Predevelopment Conditions

Before extensive ground-water development, the primary source of recharge to the Chicot aquifer system was precipitation on the outcrop areas. Most of this recharge was discharged locally to perennial streams and rivers or by evapotranspiration. Water that was not discharged locally entered the aquifer system as recharge. This water moved downgradient toward discharge areas in the Atchafalaya, Sabine, and lower Vermilion River basins and the coastal marshes. Recharge rates are relatively high in the outcrop area because surface clay is thin or absent. According to Jones and others (1956, p. 228), a study from 1946 to 1951 of the Bundick and Whiskey Chitto Creeks in the outcrop areas in Allen and Beauregard Parishes indicated a recharge rate of about 0.8 in/yr in an area where little ground-water development had taken place.

Under predevelopment conditions, water in the confined downgradient parts of the aquifer system discharged upward to shallower aquifers or the surface because hydraulic head generally increased with depth. Head increased with depth because each successively deeper aquifer in the system crops out farther north at a higher altitude. Figure 5 shows highly generalized lateral flow paths in the Chicot aquifer system under predevelopment conditions. Upward flow was greatest through sandy interconnections where confining clays between the aquifers are thin or missing. Natural ground-water discharge occurred in the coastal wetland areas and along the Atchafalaya, Mermentau, lower Vermilion, and Sabine Rivers, where water moved upward from the aquifer through the surface clays. Discharge was most concentrated where the Atchafalaya and lower Vermilion Rivers have breached the surface clays confining the Chicot aquifer system. The part of the coastal area that received natural ground-water discharge was defined approximately by Harris and others (1905) as the part of coastal Louisiana and Texas where wells flowed in the early 1900's. (See fig. 5.)

Pumpage

The pumpage of water for irrigation, municipal, and industrial purposes is the largest source of stress on the Chicot aquifer system and the Evangeline aquifer in southwestern Louisiana. Rice irrigation utilizes most of the water pumped. Annual rates of pumping for all purposes from the Chicot aquifer system and the upper Evangeline aquifer are shown in figure 6 for the period 1946-85. The total ground-water pumpage for 1985 is shown but was not used in the development of the digital flow model because detailed pumpage data were not available.

Irrigation

During 1980 nearly 90 percent of the ground water pumped in southwestern Louisiana was used for rice irrigation. About 500,000 acres of rice were planted in 1980. Of this acreage, 60 percent was irrigated with ground water and the remainder with surface water (Hill and others, 1981). Almost all ground water used for irrigation comes from the upper Chicot aquifer. Both ground water and surface water are used in some areas and estimation of the ground-water pumpage is difficult. Irrigation pumpage data from 1900 to 1960 used in this report were originally compiled for an analog model for southwestern Louisiana and eastern Texas (A.L. Zack and A.N. Turcan, U.S. Geological Survey, written commun., 1975).

Annual agricultural reports (Fielder and Parker, 1963; Fielder and Guy, 1978; Fielder and Nelson, 1983) supplied the acreage irrigated from 1960

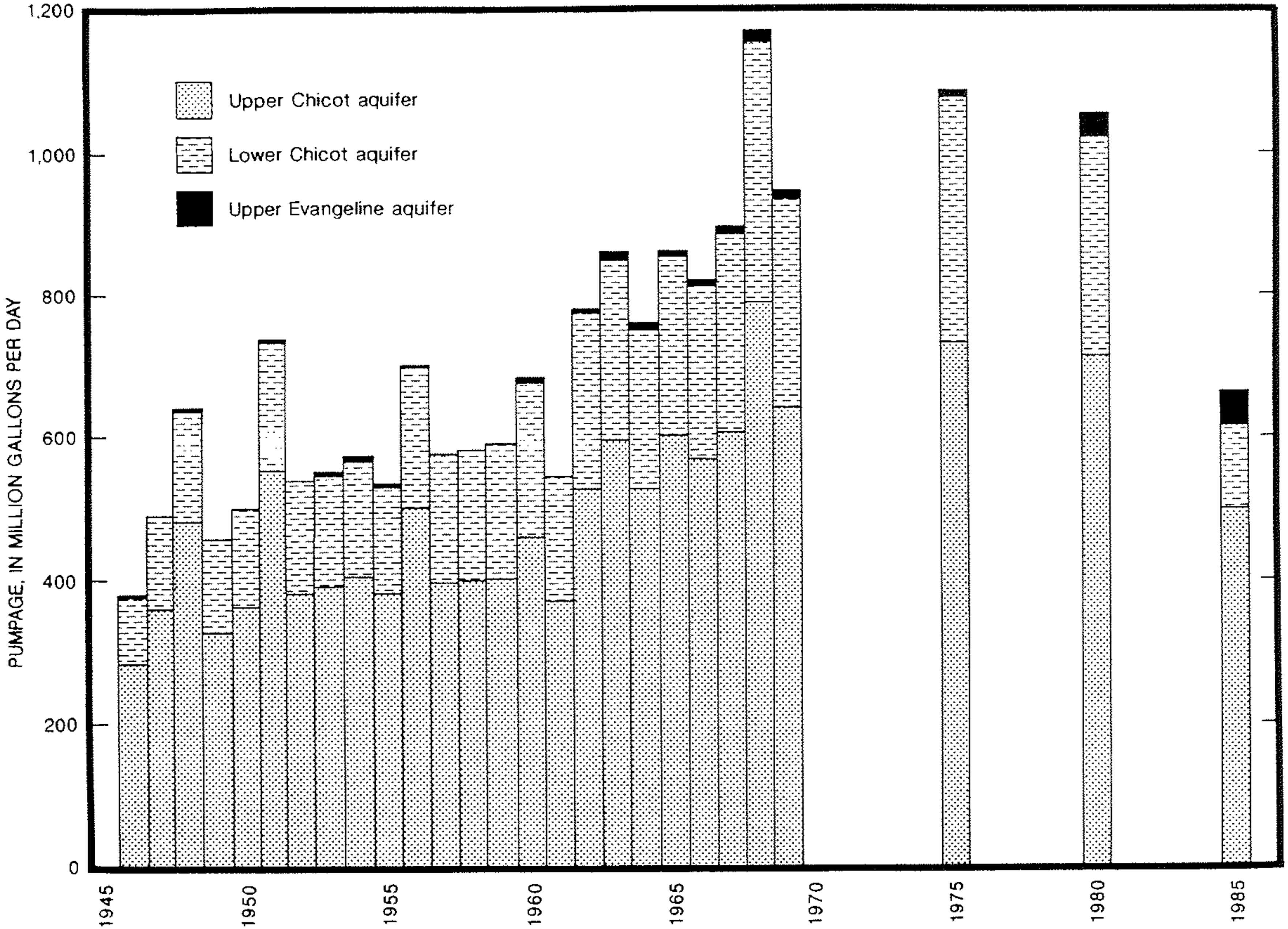


Figure 6.--Total pumpage from the Chicot aquifer system and the upper Evangeline aquifer within the study area.

to 1980. Remote-sensing techniques, established by Neal (1980), differentiated the acreage irrigated by ground water from that irrigated by surface water. Acreage estimates used to compute irrigation withdrawals were made from a photograph taken April 28, 1978, from the Landsat satellite (Eversull, 1986). By relating the distribution of acreage irrigated by ground water in 1978 to the annual rice acreage planted, an estimate of ground-water irrigated acreage was made for each year. The estimated acreage times the application rate (the average quantity of water applied per acre per irrigation season) provided the annual irrigation usage from 1960 to 1980. The application rate was estimated using a relation between rainfall and ground-water application rate developed by Zack (1971, fig. 2).

Industrial and Municipal

Industrial and municipal pumpage data have been collected in Louisiana at 5-year intervals in connection with State and national water-use surveys. These data are collected individually for each user, so pumpage can be assigned to a specific location.

About 70 percent of the industrial pumpage in southwestern Louisiana is from the "500-foot" sand for use by the petrochemical industry in the Lake Charles industrial area. The 5-year interval pumpage records for the Lake Charles area indicate that industrial and municipal pumpage averaged 75 Mgal/d in 1965, 100 Mgal/d in 1970, and 85 Mgal/d in 1975 and 1980.

Effects of Development

The first potentiometric map documenting the effect of pumpage of the Chicot aquifer system was based on data collected in 1944 (Jones and others, 1956, pl. 16). This map (fig. 7) shows a broad trough in the potentiometric surface in the rice-growing area caused by pumping for irrigation and a cone of depression in the potentiometric surface at Lake Charles caused by pumping for the petrochemical industry. Records indicate that water levels in wells declined, on average, about 1 ft/yr from 1900 to 1981 in the Lake Charles and rice-growing areas.

As water levels declined, less water was discharged locally and flow increased southward toward the pumping centers. Also, as water levels declined beneath the coastal marshes, wells ceased flowing and the former discharge areas became recharge areas. Movement of water through the surface clays reversed, and water began moving downward from the marshes to recharge the aquifer system. The Atchafalaya River also became a source of recharge for the Chicot aquifer system, particularly where the surface clays had been breached and where the river is in direct contact with the upper Chicot aquifer (Jones and others, 1956).

Vertical leakage of water also increased through the lower confining clays. Similarities in water-level fluctuations in the upper and lower Chicot aquifers in the rice-growing area near Crowley, in Acadia Parish, Louisiana (fig. 8), demonstrate the good hydraulic connection between aquifers in the rice-growing area. In the vicinity of observation well

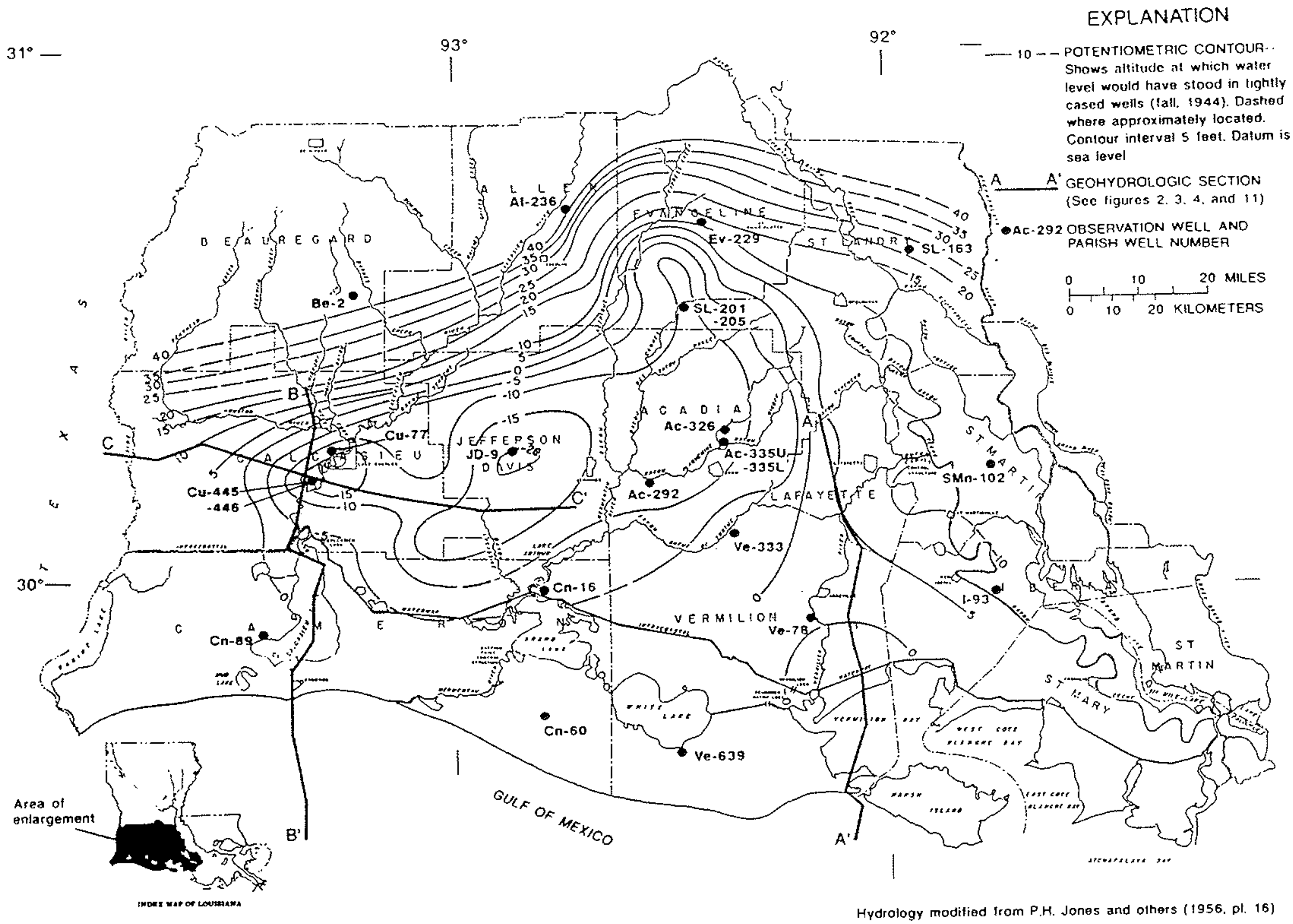
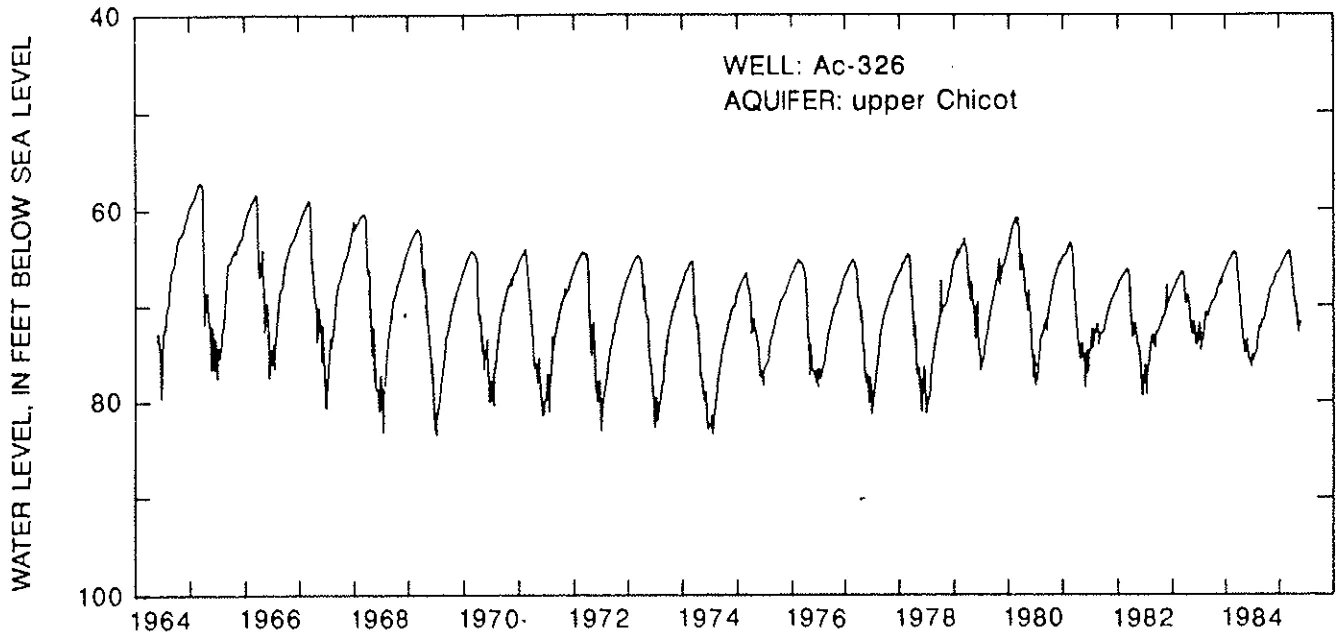


Figure 7.--The lowest water levels in the Chicot aquifer system during the fall of 1944.



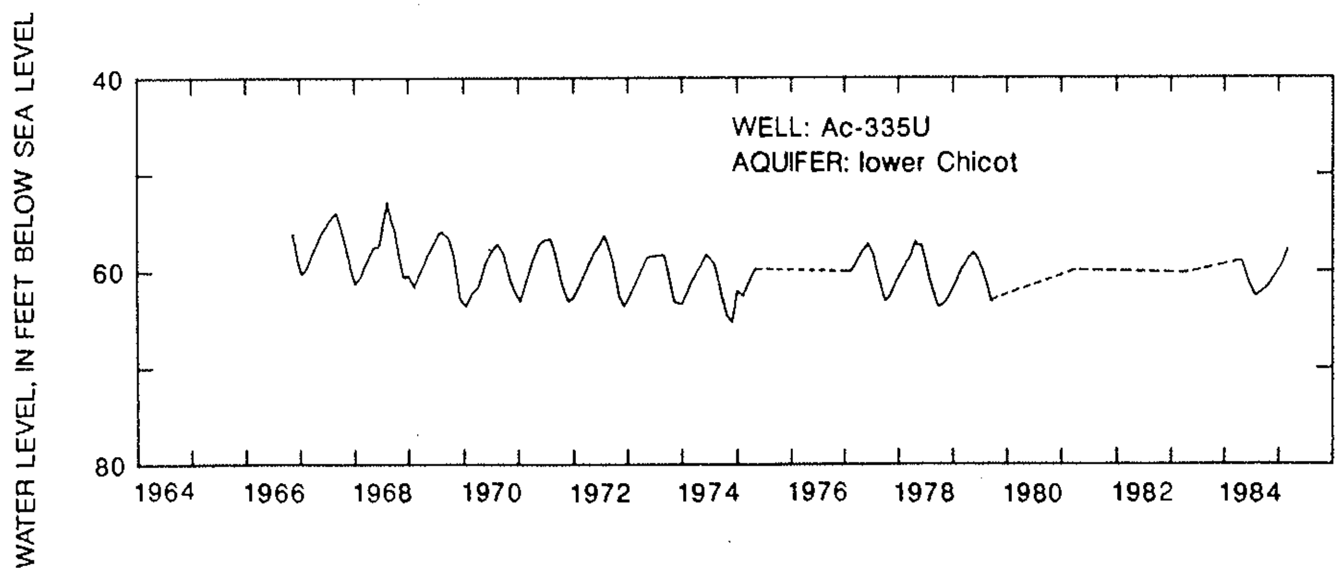


Figure 8.--Comparison of water levels in the upper and lower Chicot aquifers in Acadia Parish.

Ac-335U (fig. 7), there is no pumping for rice irrigation from the lower Chicot aquifer. However, seasonal water-level fluctuations caused by irrigation pumpage from the upper Chicot aquifer, reflected in the hydrograph of observation well Ac-326, are apparent in the hydrograph of well Ac-335U that was screened in the lower Chicot aquifer.

In the Lake Charles area, the "500-foot" sand is the most heavily pumped aquifer and has the lowest water levels in the Chicot aquifer system. Average pumpage from the "500-foot" sand is more than 10 times that from the "700-foot" sand and about 30 times greater than that from the "200-foot" sand. During 1980, pumpage from the "500-foot" sand was more than 40 Mgal/d in the vicinity of well Cu-445, whereas pumpage from the "700-foot" sand was less than 1.0 Mgal/d in the vicinity of well Cu-446 (fig. 7). A comparison of water levels and water-level fluctuations in these two wells in the "500-foot" and "700-foot" sands in the southern part of the industrial area (fig. 9) indicates a good hydraulic connection. Vertical leakage to the "500-foot" sand occurs from both the "200-foot" and "700-foot" sands.

SIMULATION OF THE GROUND-WATER FLOW SYSTEM

Description of Model

A finite-difference, digital ground-water flow model was developed to simulate flow in the Chicot aquifer system under predevelopment conditions and to estimate the effects of various simulated pumping stresses imposed on the system under current and future conditions. As previously discussed, the Chicot aquifer system is a composite of interbedded sands and clays where vertical flow components are as important as horizontal ones. Considering the nature of this system, a three-dimensional model was deemed necessary for an accurate simulation.

The U.S. Geological Survey's modular finite-difference model (McDonald and Harbaugh, 1988) was selected to simulate flow in the Chicot aquifer system. This model is well documented, has been tested on a wide range of problems, and has the features needed to simulate the Chicot aquifer system under both steady-state and transient-flow conditions.

The use of this finite-difference model, or any other, requires the discretization of the system into a series of blocks. This breakdown is done in layers, rows, and columns (fig. 10). The sizes of these blocks were based on the local stresses imposed on the system and the degree of resolution desired in the model. Relatively large blocks were used in this model because it was designed to describe a large regional system. This coarse discretization causes some discrepancies to occur between observed and calculated water levels in highly stressed areas where large, local water-level variations exist; however, use of smaller blocks would not have enhanced the understanding of the regional flow system.

Five layers were used in this model. Layer 1 is used to represent the boundary of the aquifer system as described in the section Boundary Conditions. Most of the Chicot aquifer system could be simulated by one layer

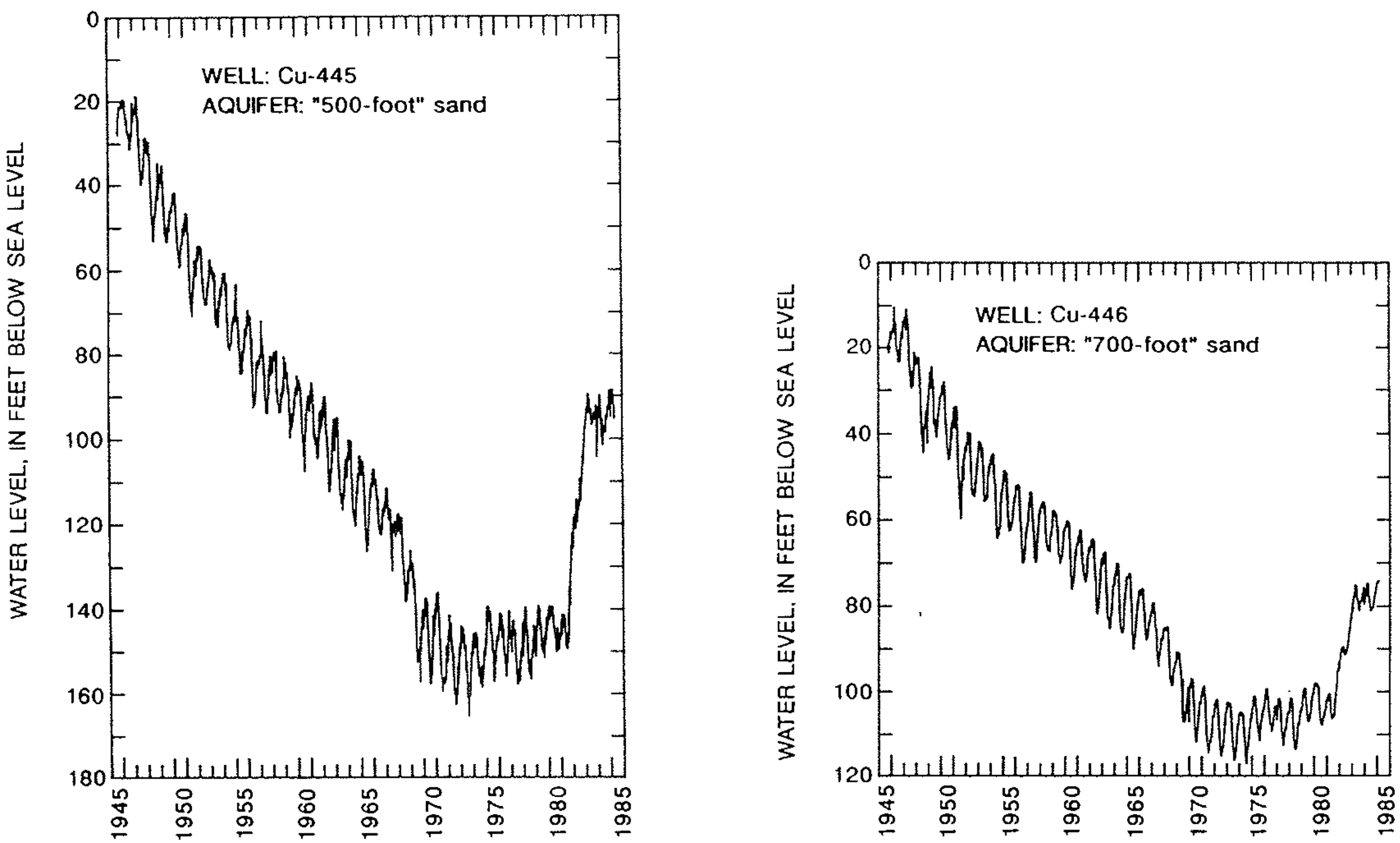


Figure 9.--Comparison of water levels in the "500-foot" and "700-foot" sands in the Lake Charles area, Calcasieu Parish.

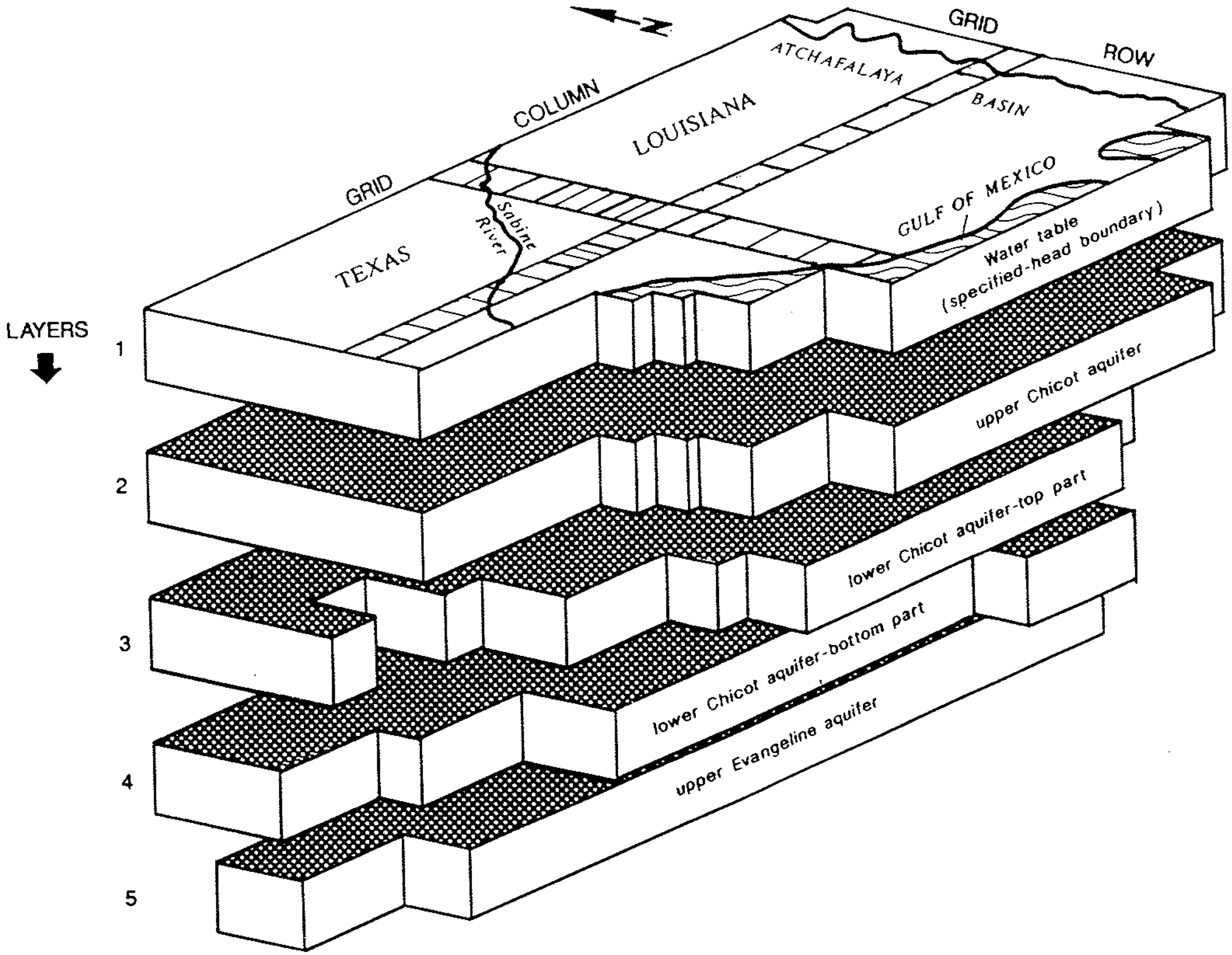


Figure 10.--Generalized schematic diagram of the digital model used to describe the Chicot aquifer system.

because large areas consist of a single massive sand. However, the aquifer system was simulated as three layers in this model because in the Lake Charles area the aquifer system consists of three distinct hydrologic units, the "200-, 500-, and 700-foot" sands which are separated by confining clay beds. In the model, layer 2 represents the upper Chicot aquifer which includes the "200-foot" sand in the Lake Charles area. Layer 3 represents the upper part of the lower Chicot aquifer and the "500-foot" sand. Layer 4 represents the lower part of the lower Chicot aquifer and the "700-foot" sand. Layer 5 represents the upper part of the Evangeline aquifer. Layer 5 is used in the model only as a water source or sink for the Chicot aquifer system, but lateral flow and potential are calculated in the layer. This study did not include a simulation of flow in the entire Evangeline aquifer. The relation of the model layers to geohydrologic units is shown in a north-south section through the Lake Charles area (fig. 11) and in table 1.

The confining units between sands are represented in the model by leakance values assigned between each model layer. Leakance is the vertical hydraulic conductivity of the clay bed divided by the thickness of the bed. The leakance values control the vertical flow of water between model layers.

The model grid has 14 rows of 21 columns and measures 197 mi east-west by 100 mi north-south (fig. 12). The grid is oriented parallel to the outcrop of the Chicot aquifers in Louisiana. Variably-spaced blocks were used to obtain more detail in highly stressed areas such as Lake Charles. The blocks range in size from 16 to 169 mi^2 with the largest blocks being located at the periphery of the model. The large blocks are acceptable because they are located in areas of little or no stress and beyond the main areas of interest. Values of aquifer hydraulic properties assigned to the center of each block, defined as the node, represent an average of the values within the block. Some of the blocks are inactive because they are in areas where the aquifer represented by its corresponding layer does not exist (fig. 12). Model layer 2, which represents the upper Chicot aquifer, is the most areally extensive layer, whereas model layer 5, which represents the upper Evangeline aquifer, is the least extensive (fig. 13).

Boundary Conditions

Proper representation of model boundaries is one of the most important aspects in the simulation of an aquifer system. Model boundaries must represent actual hydrologic boundaries that affect an aquifer system as accurately as possible or be far enough away from any simulated stresses to not significantly affect the simulation results.

The upper boundary of the model consists of a specified-head layer (layer 1) overlying the 4 layers representing the Chicot aquifer system and the upper Evangeline aquifer. The water level assigned at each node in layer 1 is the long-term average altitude of the water table at the node. Layer 1 acts as a source or sink for all water entering or leaving the flow system, except for flow across other boundaries and water removed by pumpage. Use of a specified-head upper boundary is acceptable because there has been no

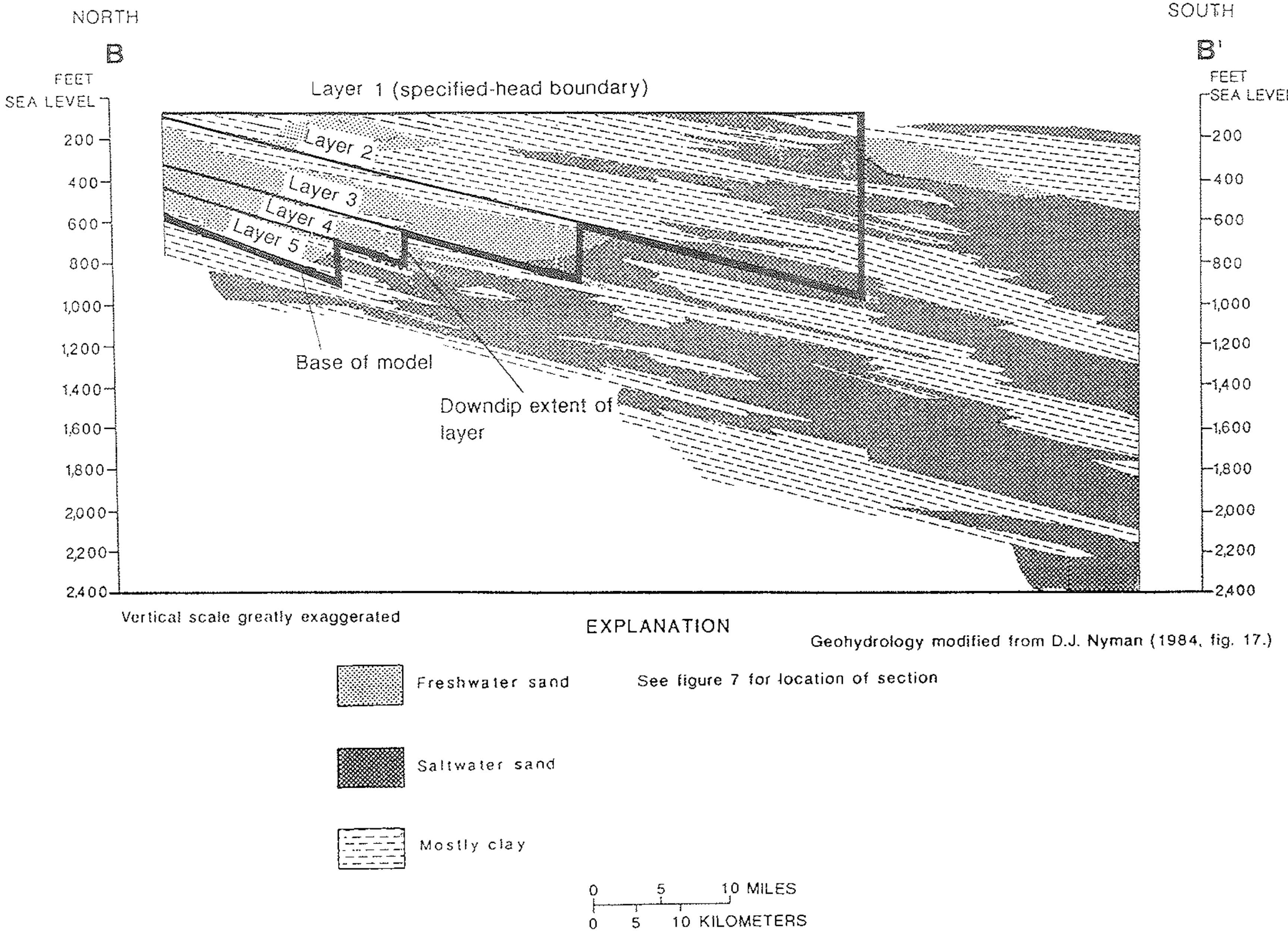


Figure 11.--Geohydrologic section B-B' in southwestern Louisiana showing layering scheme used in modeling the Chicot aquifer system.

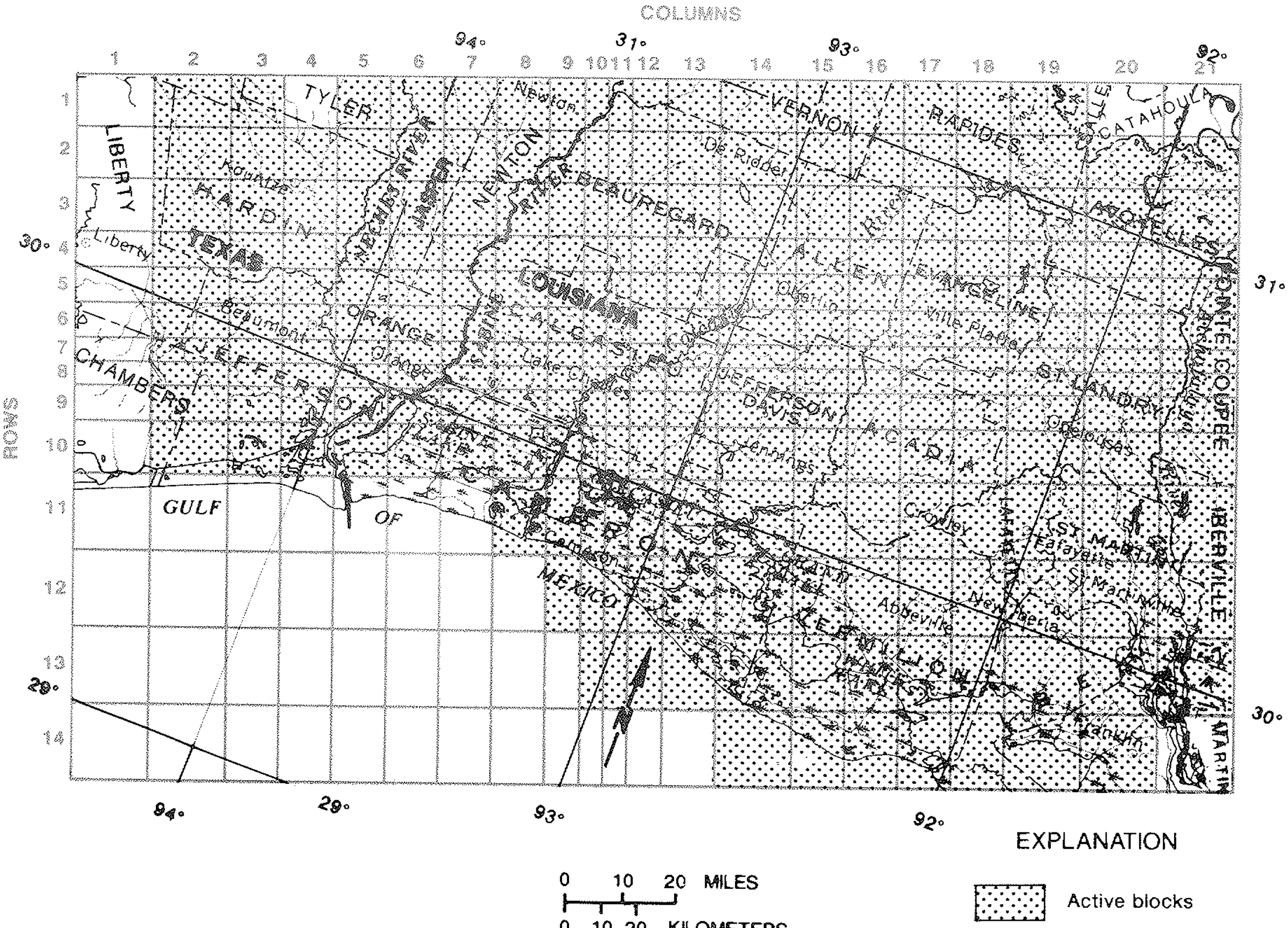
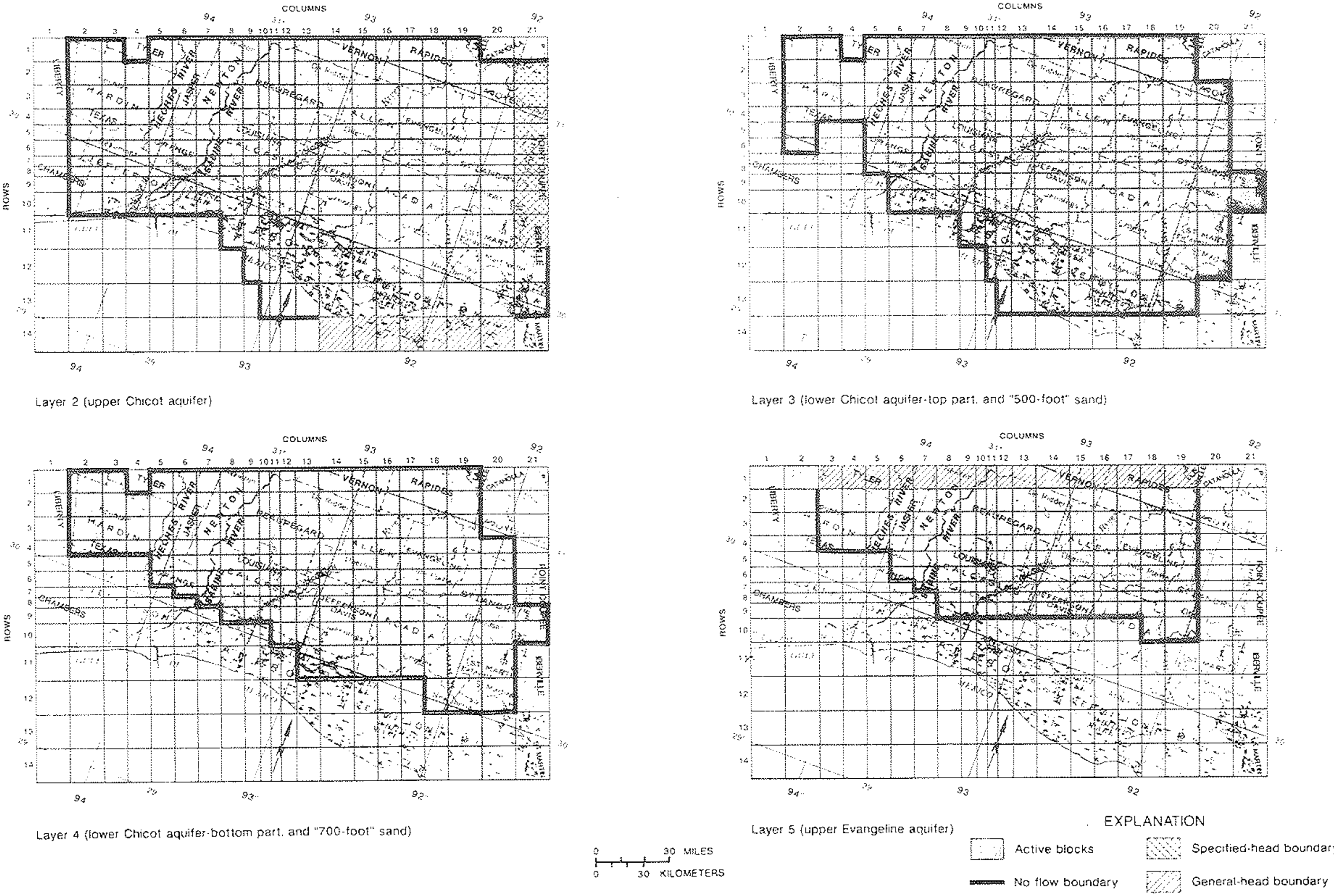


Figure 12.--Grid and areal extent of the model.



Layer 2 (upper Chicot aquifer)

Layer 3 (lower Chicot aquifer-top part, and "500-foot" sand)

Layer 4 (lower Chicot aquifer-bottom part, and "700-foot" sand)

Layer 5 (upper Evangeline aquifer)

Figure 13.--Boundary conditions and extent of model for layers 2 through 5.

significant decline in water-table altitudes as a result of pumping through 1981. Streams draining the recharge areas have high base flows, indicating that recharge is being rejected by the Chicot aquifer system under 1981 conditions.

The northern and eastern boundaries of the model coincide with hydrologic boundaries of the Chicot aquifer system (fig. 13). The northern boundary is no flow because it is the northern limit of the Chicot aquifer system. The eastern boundary of the model coincides with the Atchafalaya River, which is well connected to the upper Chicot aquifer. The river acted as a drain for the aquifer under predevelopment conditions but under current conditions is primarily a source due to flow induced by pumpage. In either instance, the long-term mean stage of the river can be treated as a constant despite seasonal variations that are unimportant to the relatively long time scale used in the model simulation. Results are calculated for the average response of the Chicot aquifer system. Pumping from the Chicot aquifer system has negligible effects on the river stages, as the greatest pumping rates for the entire Chicot aquifer system are less than 1 percent of the mean flow rate of the Atchafalaya River at Simmesport, Louisiana (Carlson and others, 1985, p. 305). The effects of the Atchafalaya River are simulated in the model by making the eastern boundary a specified-head boundary in the upper Chicot aquifer with the head at each node specified as the average stage of the river in that node. Each of the deeper aquifers is simulated as having a no-flow boundary along its eastern side. The eastern boundaries of deeper layers are treated as no flow because little or no water crosses the axis of the river and future ground-water development near the river is not expected.

The southern boundary of the flow system is located, for modeling purposes, where the total dissolved-solids concentration of water in an aquifer is equal to or greater than 10,000 mg/L. Parts of the aquifer system containing water with a dissolved-solids concentration of 10,000 mg/L and greater are treated as stagnant relative to the time scale of the model and are represented as no-flow zones. Thus, the southern boundary of each aquifer is simulated as no flow at the freshwater-saltwater interface in that aquifer.

The southeastern part of the model in layer 2 is an exception to the southern no-flow boundary. Here the aquifer contains freshwater to the edge of the model area. Water levels have declined and are expected to continue declining. Neither a no-flow nor a specified-head boundary is appropriate. To better approximate the conditions that occur in this region, a general-head boundary was used.

The general-head boundary allows water to flow to or from an external source. The working assumption of the general-head boundary is that the external flow into or out of the model is one dimensional between an external source and the adjacent model block (McDonald and Harbaugh, 1988, p. 11-1). The flow is controlled by a conductance value which is based on the distance from the external source to the model block and the conductivity of the intervening material and by the difference between the head at the external source and the head in the model block.

The bottom of layer 5 is a no-flow boundary. The Evangeline aquifer crops out farther north than the Chicot aquifer system, and a general-head boundary is used along the northern edge of layer 5 to allow water to enter the model from the outcrop area of the Evangeline aquifer.

The western model boundary lies along a ground-water divide between cones of depression at Beaumont and Houston, Texas (Carr and others, 1985). Water flows along the divide primarily from north to south with little flow to the east or west. This boundary is treated as no flow in all of the modeled aquifers. Under the stresses imposed during the calibration period (1900-1981), this is a satisfactory approximation. If large stresses are imposed or the existing pumpage patterns are varied greatly in the western model area, this boundary condition may not properly simulate actual conditions. In either instance, careful consideration should be given to whether boundary-induced errors related to this boundary are acceptable. One possible alternative would be to change the western no-flow boundary to a general-head boundary.

Hydraulic Properties

Initial estimates of values for lateral hydraulic conductivity and storage used in the model were based on previous studies (Carr and others, 1985; Harder and others, 1967; Harder, 1960; Jones and others, 1956; Whitfield, 1975) and results of aquifer tests conducted within the study area (Martin and Early, 1987). The range of transmissivity and storage coefficient for aquifers in the study area is given in table 2. Final calibrated values of transmissivity and storage coefficients are different than those calculated from aquifer tests because of variations in sand thickness and heterogeneities of the aquifers.

No aquifer tests have been performed in the study area that permit calculation of leakance or the vertical hydraulic conductivity of the confining units. Laboratory studies of clay cores from the Lake Charles industrial area (F.S. Riley, U.S. Geological Survey, written commun., 1973) indicate that clay below the "200-foot" sand had a vertical hydraulic conductivity of 7.6×10^{-6} ft/d under a confining pressure equivalent to a 400 ft depth of burial and 1.5×10^{-3} ft/d at atmospheric pressure. Clay cores from below the "500-foot" sand had vertical hydraulic conductivities averaging 3.8×10^{-6} ft/d under a confining pressure equivalent to a 600 ft depth of burial and 8.9×10^{-4} ft/d at atmospheric pressure. Vertical hydraulic conductivity of confining units determined from other flow models of the Chicot aquifer system in Texas ranged from 3.2×10^{-5} to 4.6×10^{-3} ft/d (Carr and others, 1985, p. 45). These values were used as initial estimates in this model.

Model Calibration

The model was calibrated to historical water levels and water budgets by adjusting transmissivities, vertical leakances, and storages to minimize differences between simulated and observed values. The root-mean-square error

Table 2.--Range of thickness, transmissivity, and storage coefficient for aquifers in southwestern Louisiana and southeastern Texas

Aquifer	Thickness (feet)	Transmissivity (feet squared per day)	Storage coefficient (dimensionless)	References
Rice-growing area and Atchafalaya River basin, southwestern Louisiana				
Chicot aquifer (undifferentiated).	100-600	10,000-135,000	0.0004-0.003	Jones, and others (1956, p. 221) Harder, and others (1967, p. 7)
Upper Evangeline aquifer.	(a)	1,000- 12,000	.0002	Whitfield (1975, p. 14-20)
Lake Charles industrial area, southwestern Louisiana				
"200-foot" sand.........	116-123	10,000- 16,000	(b)	Harder (1960, p. 16-17)
"500-foot" sand.........	125-230	17,000- 37,000	.00011- .0011	
"700-foot" sand.........	140	20,000- 25,000	.00028- .0017	
Southeastern Texas				
Chicot aquifer (undifferentiated).	(a)	3,000- 50,000	.0004 - .0005	Carr, and others (1985, p. 25)

[a] Thickness not determined.
[b] No data available.

(RMSE) between observed and computed water levels provides a quantitative measure of the effect of changes made in the model between simulations. The RMSE is defined by:

$$\sqrt{\frac{\sum_{i=1}^{N} (h_i^o - h_i^c)^2}{N}},$$

where h^o is the observed water level; h^c is the model-computed water level; and N is the total number of water-level comparisons.

In addition to trial-and-error calibration, a statistical optimization program was applied to the model (Hugh Mitten and Alex Williamson, U.S. Geological Survey, written commun., 1987). This program automatically runs the model many times, changing the value of a single parameter for each run. Changes may be made in a parameter for the entire model, for individual model layers, or for subareas within a layer. After each run, the program statistically compares the results of that run with the results of an initial base run and with observed conditions in the aquifer system and computes a new value of the parameter that should improve the match of the model output to observed conditions in the aquifer system. This iterative process is continued until model errors are reduced to a specified level or until a specified number of iterations have been made (Durbin, 1983).

Observed base flow data are not available, so model-computed discharges to streams could not be directly evaluated. Computed flows were examined during calibration, however, to insure that results were reasonable. Model calibration was accomplished in two phases. The first phase involved steady-state calibration to match 1981 water levels. The second phase involved transient calibration to match observed changes in the aquifer system that occurred between 1900 and 1981.

Steady-State Simulation

Steady-state conditions were assumed to exist in the aquifer system in 1981. This assumes that water levels were not changing with respect to time. Although this assumption was not totally correct for the entire model area, it allowed initial calibration of transmissivities and leakances in an efficient manner. Pumpage data for 1975 were used for calibration because very little change occurred between 1970 and 1981. Using this relatively highly stressed period for calibration accentuated the effects of the boundaries and of changes of transmissivities and leakances on model-computed water levels.

The ranges of uncertainty for transmissivity and leakance differ. Transmissivity values are known with a higher degree of certainty because many aquifer tests are available to determine lateral hydraulic conductivity and many well logs are available to determine aquifer thickness. Although thicknesses of confining units can be determined from the well logs, good estimates of the vertical hydraulic conductivities of the clays were not available. Thus, initial estimates of vertical leakance were subject to a broad range of uncertainty and were allowed to vary over a broad range during calibration.

Calibrated transmissivity values generally are highest in the eastern part of the model area in all layers. Values average about 80,000 ft^2/d in the rice-growing area in model layers 2 and 3. Transmissivity averages 20,000 ft^2/d in model layer 3 in the Lake Charles area.

Calibrated leakance values range from 10^{-3} to 10^{-7} inverse day (day^{-1}) throughout the model area. Leakances generally decrease from upper to lower model layers. Leakances between layers 2 and 3 are about 10 times greater in the rice-growing area than in the Lake Charles area.

Overall, water levels simulated in the model were slightly lower than measured water levels. Comparison of the RMSE results for the calibrated steady-state model (table 3) indicates that model layer 2 is better calibrated than other layers and that calibration based on RMSE's becomes less accurate with deeper layers. Direct comparison of RMSE's between model layers is not entirely valid because the number of observations differs for each model layer. The greater number of wells in the upper Chicot aquifer permits more observations and, therefore, more comparisons for model layer 2.

Model calibration also is generally more reliable in model layers and in areas having significant stress, such as layer 2 in this model. The amount of stress, in terms of ground-water pumpage, decreases in the lower model layers. Calculation of RMSE's is not essential for model calibration but makes calibration less subjective.

Table 3.--Root-mean-square error of the calibrated steady-state model

Layer	Root-mean-square error (feet)	Number of observations
2	6.0	20
3	7.6	10
4	10.6	9
5	17.8	6
All	9.7	45

Transient Simulation

The transient effects of storage in the Chicot aquifer system appear to be relatively small as shown by the rapid response of water levels to changes in pumping rates (fig. 8). The relatively large seasonal water-level fluctuations are due to pumpage for rice irrigation. Varying the pumping rate causes water levels within the system to change. If pumpage increases, water levels decline. This generates greater gradients that allow the system to take in more water at a rate matching the new pumpage. For this system, a new quasi-steady-state condition is quickly reached after each stress change.

Stress periods were selected for transient simulation so that an assumption of constant pumping rates within a period would be valid. The pumpage from 1900 to 1981 was divided into 11 stress periods: 1900-12, 1913-22, 1923-33, 1934-44, 1945-50, 1951-56, 1957-62, 1963-66, 1967-70, 1971-76, and 1977-81. The calibration period ended in 1981 because 1982 marked the beginning of a significant decrease in pumpage for irrigation across southwestern Louisiana and an accompanying rise in average water levels (fig. 14). Water-level rises also occurred in the Lake Charles area after 1981 as a result of a reduction in industrial withdrawals from the "500-foot" and "700-foot" sands as some industries converted to surface-water sources. The period from 1971 to 1981 was a time of relatively stable water levels throughout southwestern Louisiana (figs. 8, 9, and 14). Pumpage data for 1980 were used in stress period 11, 1977-81.

Transmissivity, leakance, and storage were varied during transient calibration. Steady-state calibrated transmissivities and leakance were used in the initial simulation and were not significantly changed as a result of the transient calibration. Calibrated storage values ranged from 5×10^{-3} in layer 2 in the rice-growing area to 5×10^{-4} in layer 4 along the coast.

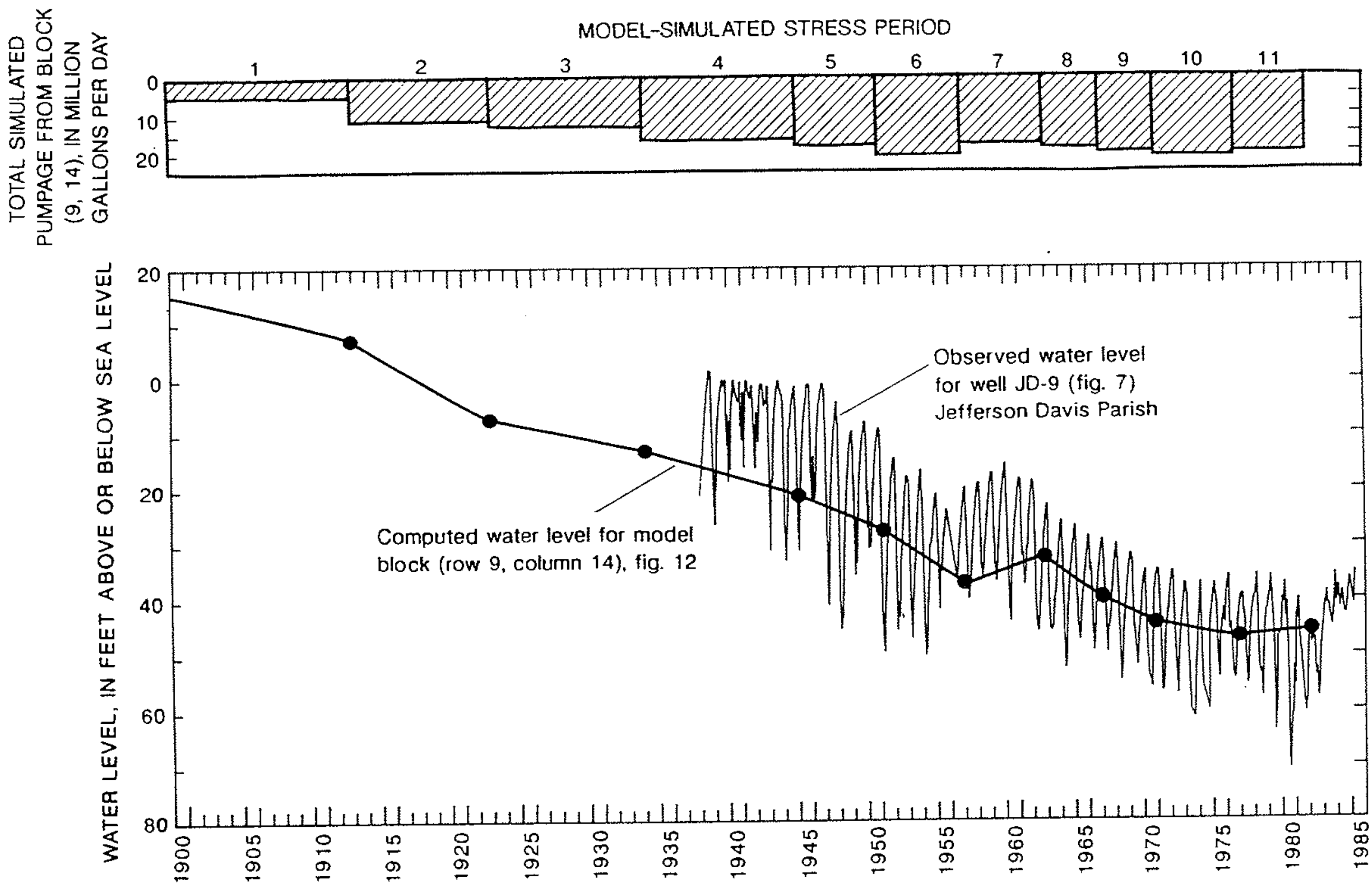


Figure 14.--Comparison of computed and observed water levels in model layer 2 (upper Chicot aquifer).

As in the steady-state calibration, RMSE's increase with deeper layers (table 4). The RMSE's from steady-state and transient simulations are not comparable because water levels from all stress periods are used for the transient comparisons. Water-level maps and vertical flows also were examined to ensure reasonable results.

Table 4.--Root-mean-square error of the calibrated transient model

Layer	Root-mean-square error (feet)	Number of observations
2	5.9	31
3	12.7	18
4	16.1	12
5	19.9	10
All	12.5	71

Computed water levels were compared to the average of the seasonal fluctuation in the hydrographs. This filtered out the large differences, as great as 40 ft, between spring and fall measurements in most rice-irrigation wells. Nineteen hydrographs were used in transient calibration: 12 in layer 2, 4 in layer 3, 1 in layer 4, and 2 in layer 5. Not every hydrograph matched well; but of the 19 compared, all model-computed hydrographs followed the trend of observed water-level rises and declines. The hydrograph of well JD-9 (fig. 14) corresponded well with the model results.

Hydrographs from the Lake Charles area proved to be the most difficult to match and showed the greatest discrepancies between observed and model-computed water levels. The high density of pumping wells in the "500-foot" sand (model layer 3) causes a significant amount of well interference that is superimposed on the average water-level decline. The discrepancy between observed and model-computed water levels is seen for well Cu-445 (fig. 15) which is in the "500-foot" sand. Well Cu-446 (fig. 16) in the "700-foot" sand (model layer 4) in the Lake Charles area showed the worst match of observed to model-computed results, but the computed water levels still follow the general trend of the measured water levels.

Model Results

After transient calibration, a steady-state simulation without pumpage was completed to represent predevelopment conditions. Simulated water levels were checked by comparison to water levels measured in the early 1900's (Harris and others, 1905). Results from the predevelopment simulation were compared with the 1981 transient-simulation results and show that:

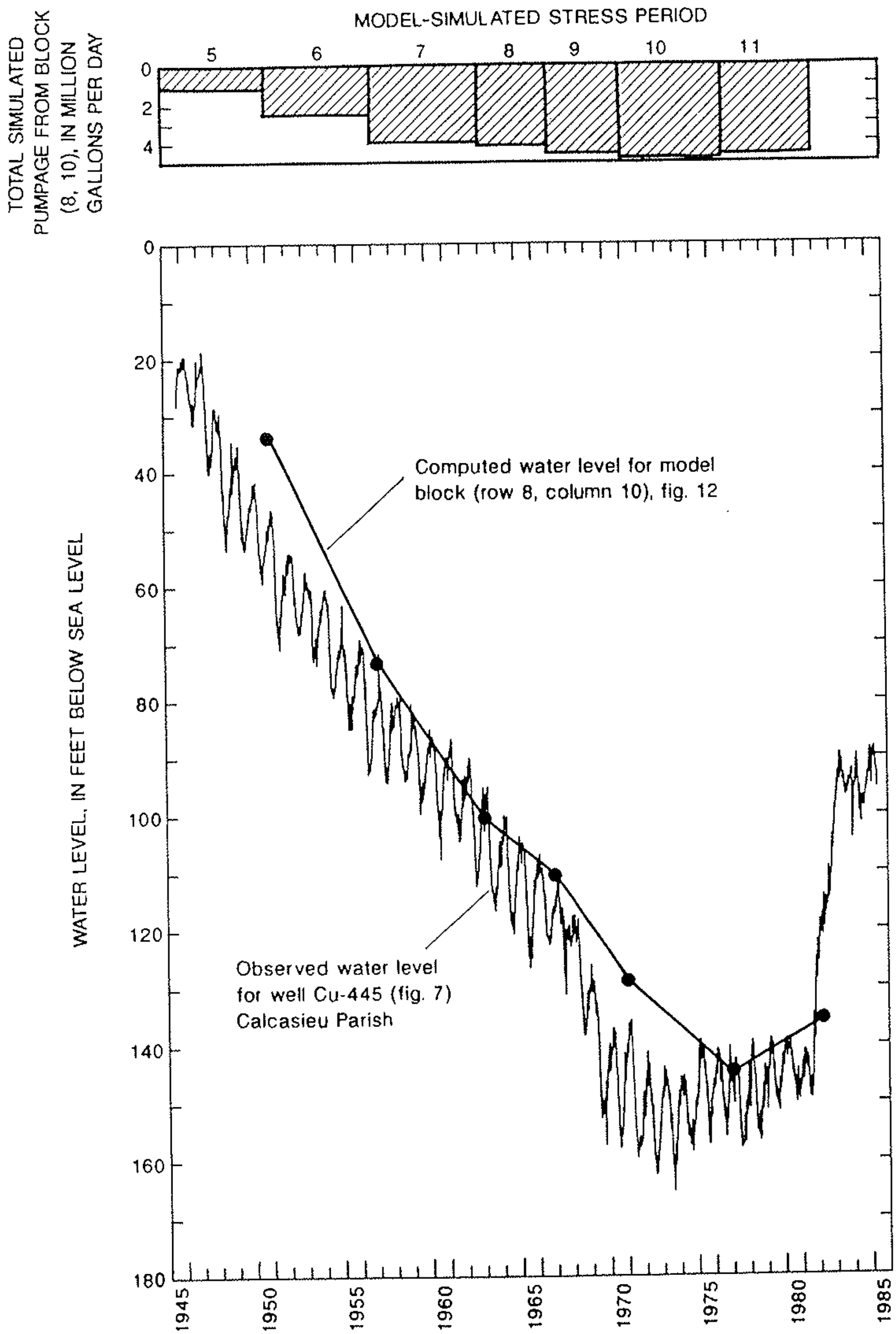


Figure 15.--Comparison of computed and observed water levels in model layer 3 ("500-foot" sand).

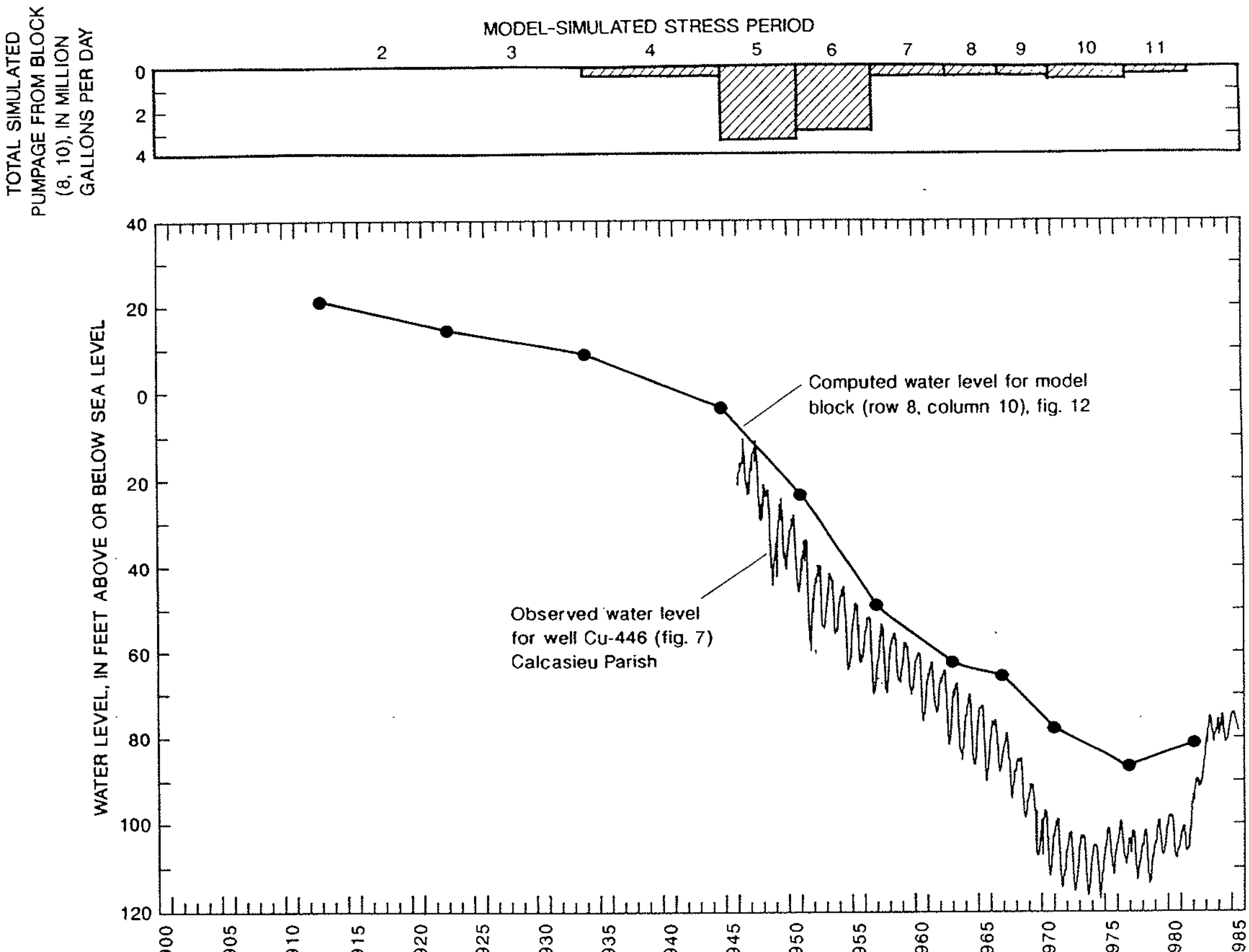


Figure 16.--Comparison of computed and observed water levels in model layer 4 ("700-foot" sand).

1. Flow patterns in the Chicot aquifer system have been significantly altered downgradient from the outcrop.
2. Total flow in the aquifer system has greatly increased (approximately fourfold).
3. Water levels have been lowered considerably in the Lake Charles and rice-growing areas.
4. Under 1981 conditions, vertical leakage is the largest component of recharge, and water derived from aquifer storage is a relatively small part of flow in the system.

Figure 17 shows the simulated potentiometric surface of layer 2 (upper Chicot aquifer) for predevelopment conditions. Ground-water flow directions can be inferred from the map because flow is perpendicular to the water-level contour lines. The map shows that ground water flows southward from the outcrop areas toward the coast, eastward toward the Atchafalaya River basin, and toward the Neches and Sabine Rivers. The distribution of vertical flow to and from the aquifer system under predevelopment conditions is shown in figure 18; positive values indicate flow from the surface is recharging the aquifer system. Negative values indicate discharge from the aquifer system to the surface. Ground-water discharges from the aquifer system to the large marshy areas along the coast at an average rate of about 0.5 in/yr, but the discharge rate may be more than 1 in/yr in localized areas. Approximately 259 Mgal/d of water flowed through the aquifer system prior to extensive development. A generalized schematic diagram (fig. 19) shows the quantities and directions of flow in the modeled aquifer system under predevelopment conditions. Of the total recharge (about 221 Mgal/d) to the upper Chicot aquifer (model layer 2), 46 percent (about 102 Mgal/d) circulates within layer 2 and the remaining 54 percent (about 119 Mgal/d) moves downward into the lower part of the aquifer system (layers 3, 4, and 5). Only 7 percent (15 Mgal/d) reaches the upper part of the Evangeline aquifer (layer 5).

Under 1981 conditions, ground-water flow in the Chicot aquifer system converges from all directions toward pumping centers in the rice-growing area and Lake Charles. Flow patterns have been significantly altered by development (figs. 17 and 20). In the rice-growing area water levels declined, on average, 1 ft/yr from 1900 to 1981. Comparison of the distribution of recharge to and discharge from the Chicot aquifer system under 1981 conditions (fig. 21) to the predevelopment distribution of recharge and discharge areas (fig. 18) shows that development has caused most of the discharge areas near pumping centers and along the coast to change to recharge areas. Up to 6 in/yr of water recharges the Chicot aquifer system at the major pumping centers (fig. 21). Approximately 1,113 Mgal/d of water enters the aquifer system under 1981 conditions (fig. 22). This is more than 4 times the circulation prior to development. Over 90 percent of this water entering the aquifer system is discharged as pumpage. Fifty-five percent (about 585 Mgal/d) of all water entering the upper Chicot aquifer (model layer 2) in 1981 was discharged to the surface or by pumpage without moving into the lower part of the aquifer system (fig. 22). Most of the increased flow under 1981 conditions caused by pumpage is supplied by recharge from the surface. In 1981, 65 percent of the water pumped from the rice-growing area was supplied by recharge from the surface. Less than 1 percent (about 9 Mgal/d) of the water entering the aquifer system came from storage.

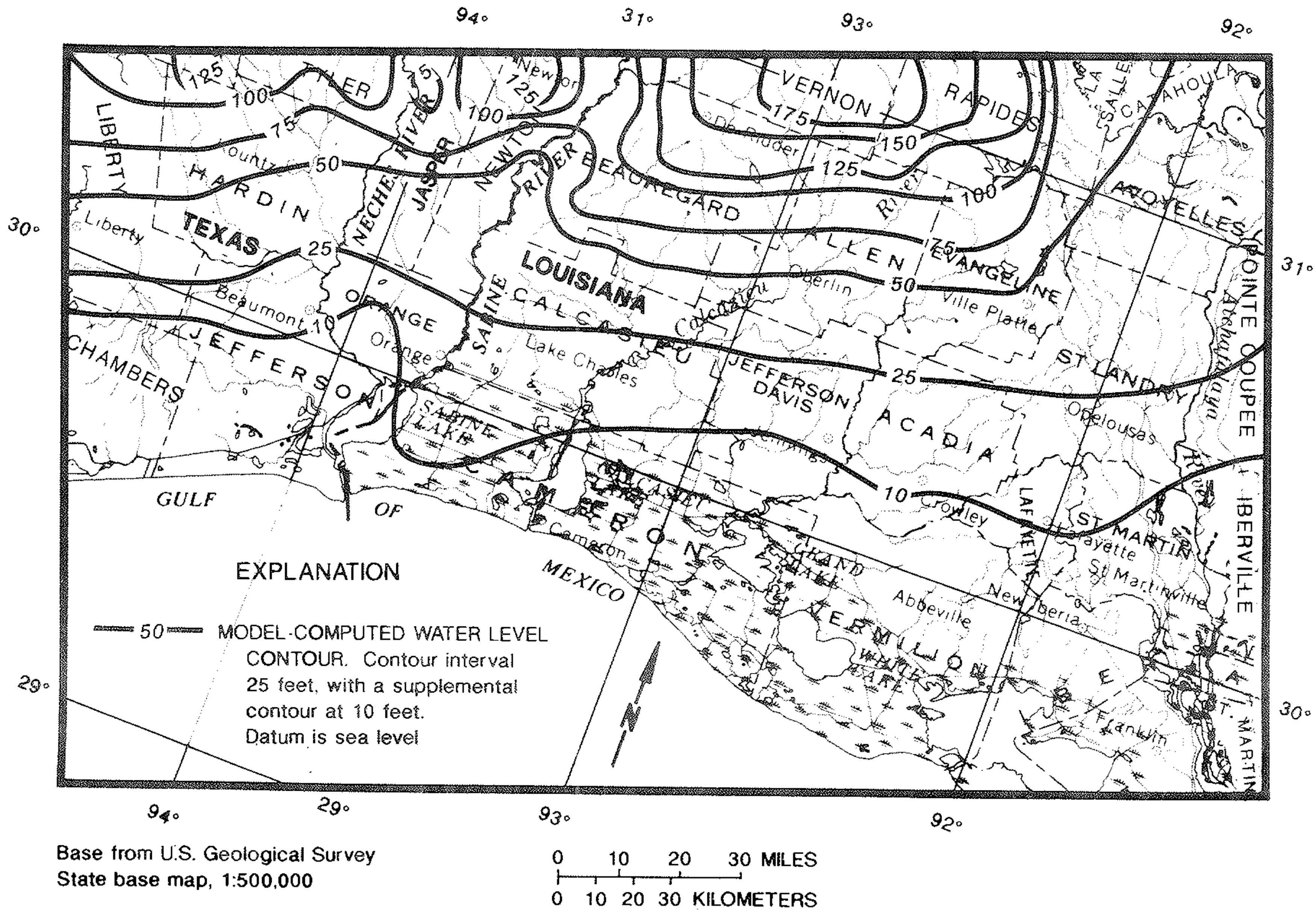
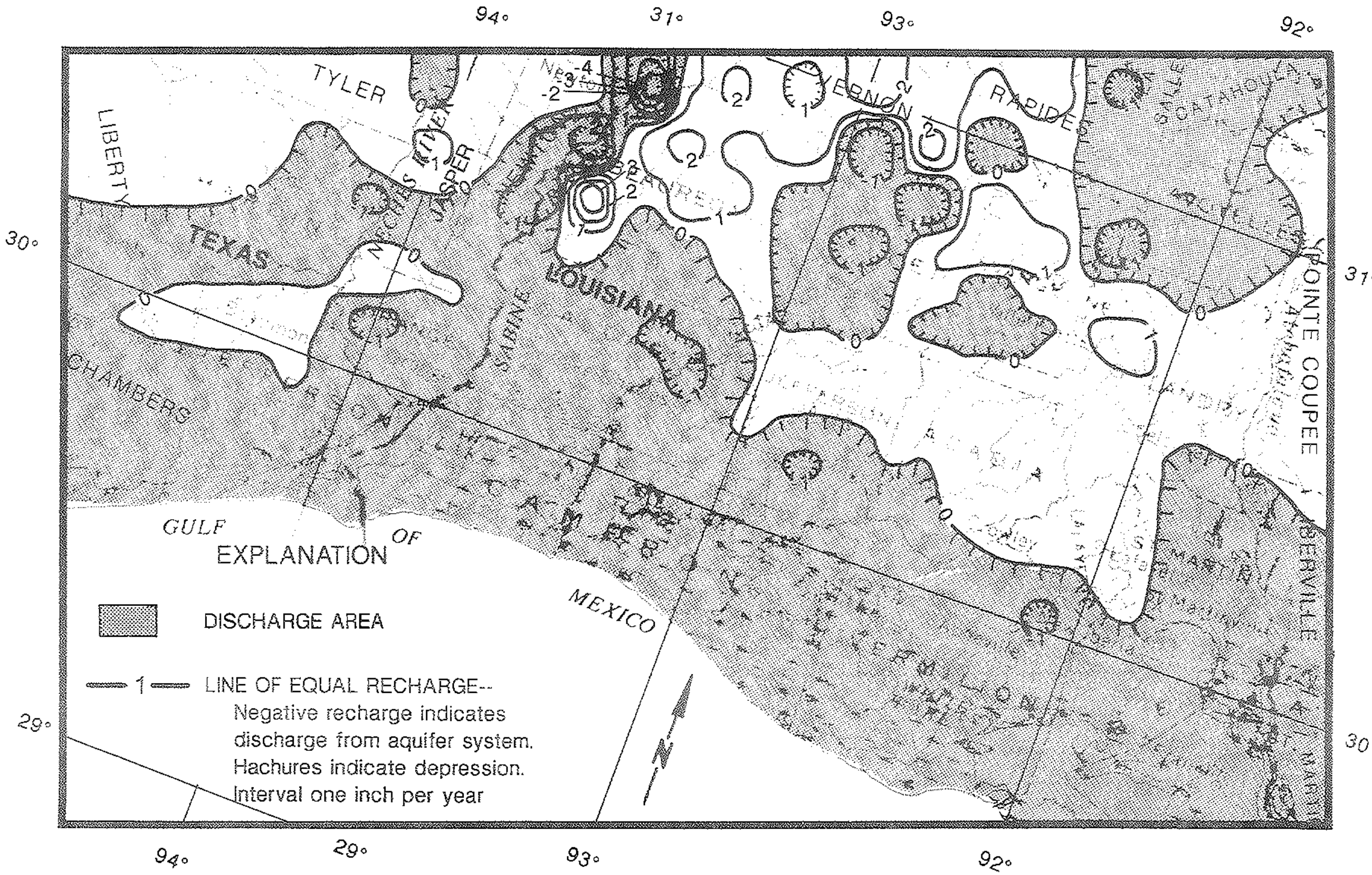


Figure 17.--Simulated predevelopment potentiometric surface of model layer 2 (upper Chicot aquifer).



Base from U.S. Geological Survey
State base map, 1:500,000

0 10 20 30 MILES
0 10 20 30 KILOMETERS

Figure 18.--Computed rates of recharge to and discharge from the Chicot aquifer system under predevelopment conditions.

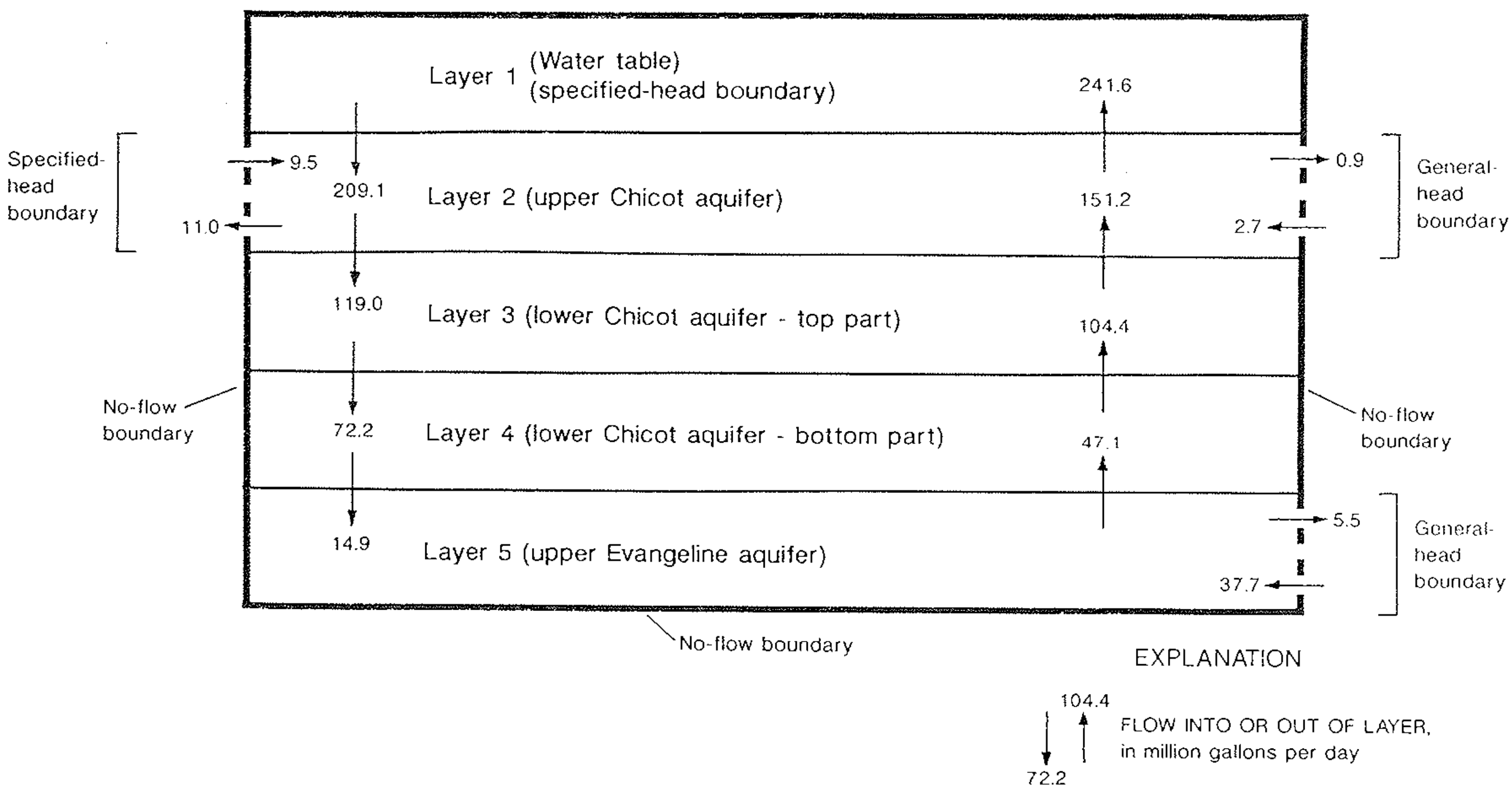
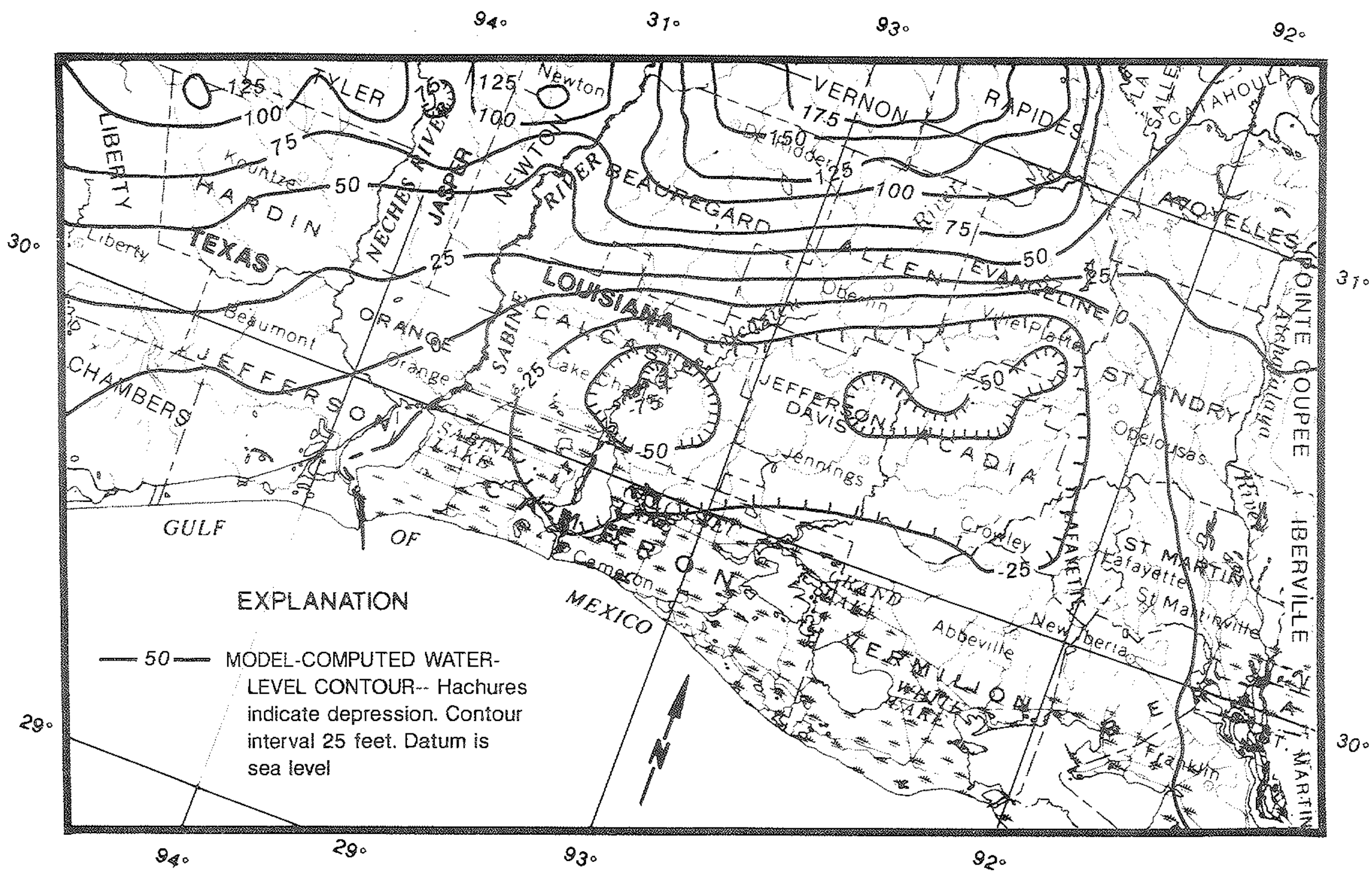


Figure 19.--The quantity and direction of simulated flow in the modeled aquifer system under predevelopment conditions.



Base from U.S. Geological Survey
State base map, 1:500,000

0 10 20 30 MILES
0 10 20 30 KILOMETERS

Figure 20.--Simulated potentiometric surface of model layer 2 (upper Chicot aquifer) for 1981.

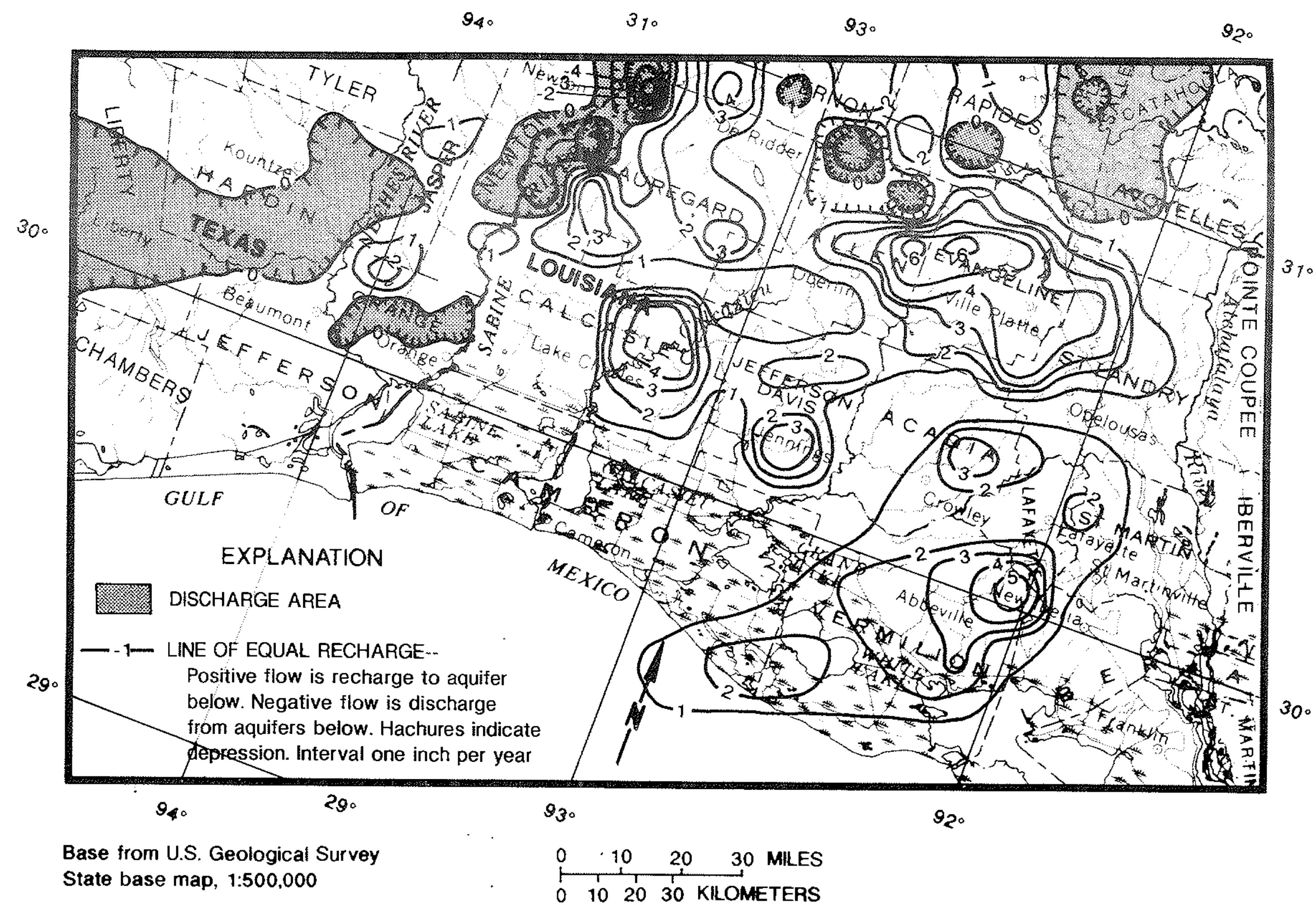


Figure 21.--Computed rates of recharge to and discharge from the Chicot aquifer system for 1981.

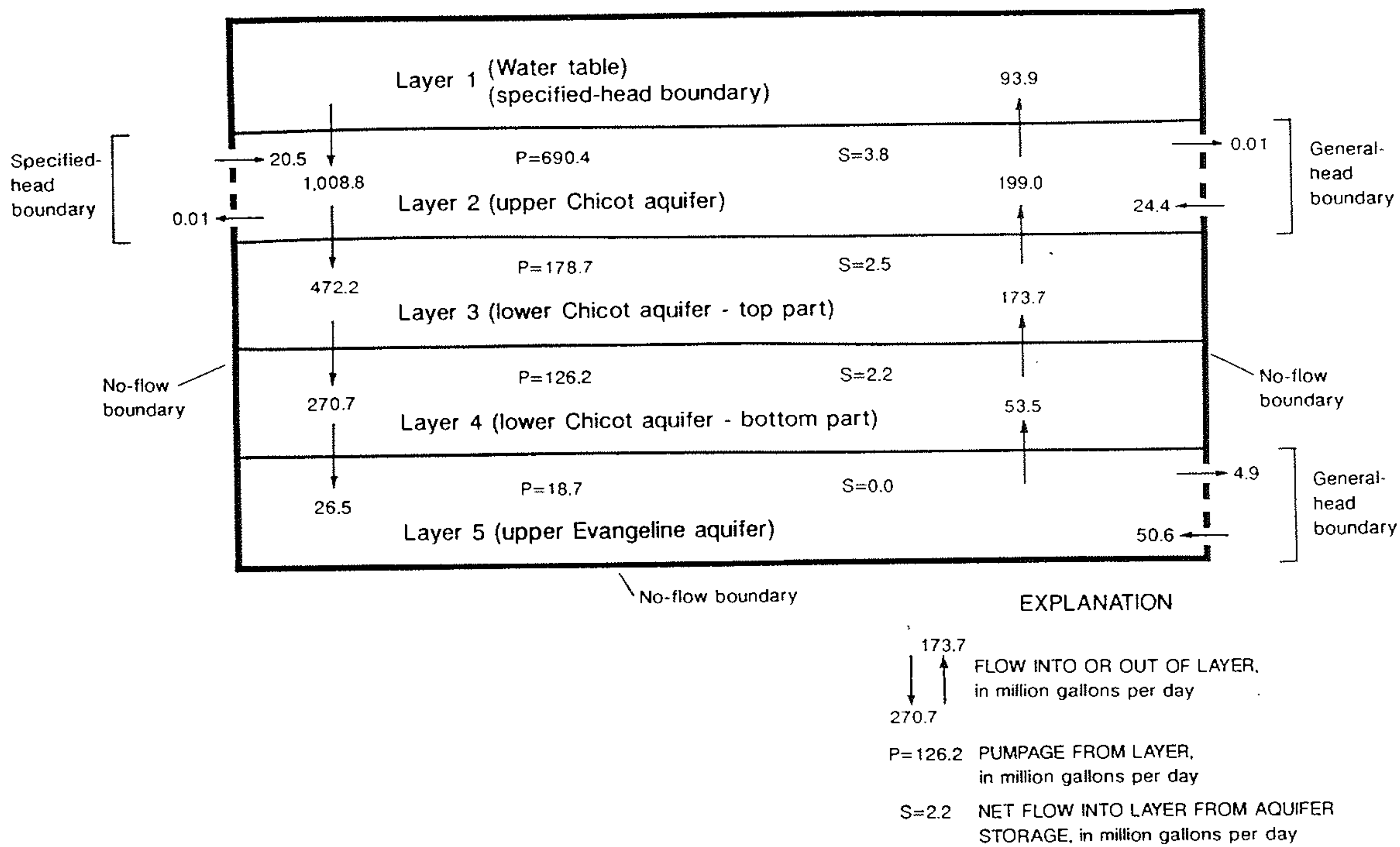


Figure 22.--The quantity and direction of simulated flow in the modeled aquifer system for 1981.

Sensitivity Analysis

Leakance, transmissivity, and storage were varied in model calibration because they were the hydraulic characteristics initially known with the least degree of certainty. To determine how each of these characteristics affected model simulation, the sensitivity of the model to adjustments in their values was examined. Model sensitivity was determined by comparing water-level RMSE results and water budgets from the calibrated model to the results of a simulation in which one of the characteristics had been changed. This process was repeated until each characteristic had been tested over a range of values. Boundary conditions and pumpage were not adjusted during calibration and were assumed to be correct, so sensitivity analysis was not performed on them.

Sensitivity of the model to adjustments in leakance between layers was examined for all model layers collectively, for layers 1 and 2 only, and for layers 2 through 5 collectively. In all instances, decreasing the leakance had a greater effect on the RMSE of water levels than an equivalent increase. Decreasing leakance between all layers by a factor of 10 produced a value of RMSE greater than 90 ft (fig. 23). The extreme sensitivity of the model to leakance reflects the strong influence of vertical recharge on the aquifer system and the predominance of pumping and points of comparison in the upper Chicot aquifer (layer 2). The model results are relatively insensitive to leakance between the lower layers. The sensitivity of the model to adjustments in all leakance values is almost identical to the sum of the two previous results.

Transmissivity, when varied for all layers, showed a symmetrical sensitivity curve (fig. 24). The minimum of this curve indicates lower transmissivity values would yield a slightly better calibration, but the slight improvement did not justify recalibrating the model. Within the range of uncertainty of the values of transmissivity, considered to be 0.5 to 2.0 times the calibrated values, the model is more sensitive to variations in transmissivity than to variations in leakance. At the lower end of the range of uncertainty associated with the values of leakance, considered to be 0.1 to 10.0 times the calibrated value, the model is more sensitive to changes in leakance than transmissivity.

Storage for all layers was varied collectively within a range of 0.01 to 5.0 times the calibrated value (fig. 25). This range was considered to be wider than the range of uncertainty. The model is sensitive to increases of storage coefficient greater than the calibrated value but is insensitive to decreases less than the calibrated value (fig. 25). The effects of storage are relatively insignificant in the Chicot aquifer system where transient conditions are of short duration. The hydrographs of rice-irrigation wells show sharp responses to pumpage changes (fig. 14). Changes in water level are directly related to changes in pumpage with little lag (fig. 26). This is because only a small part of the total flow is derived from storage.

Areally, the modeled system is more sensitive to parameter changes around Lake Charles and near the center of the rice-growing area, where pumpage is concentrated. Differences between water levels from the cali-

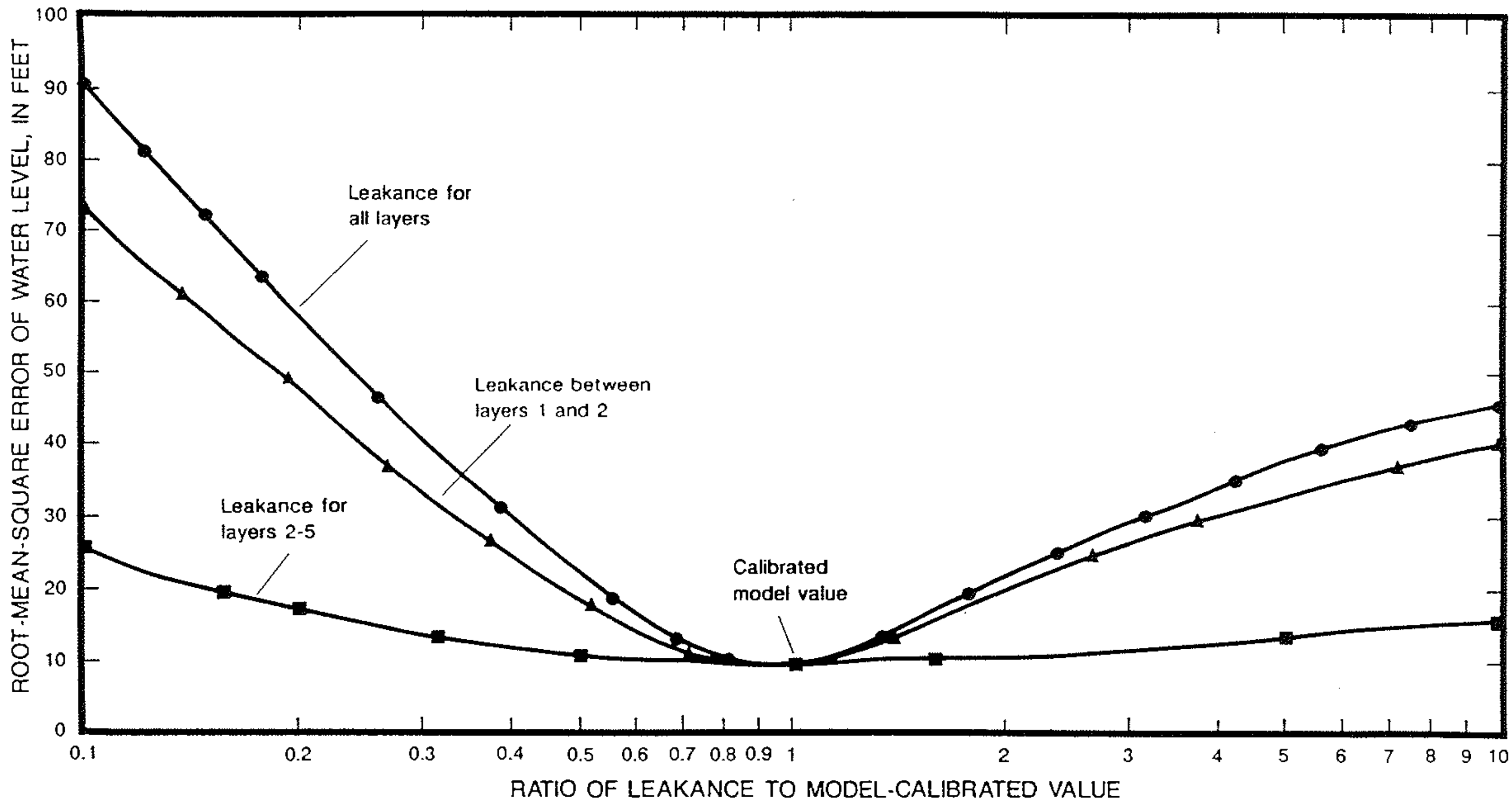


Figure 23.--Root-mean-square error of water level as a function of the ratio of adjusted leakance values to calibrated values.

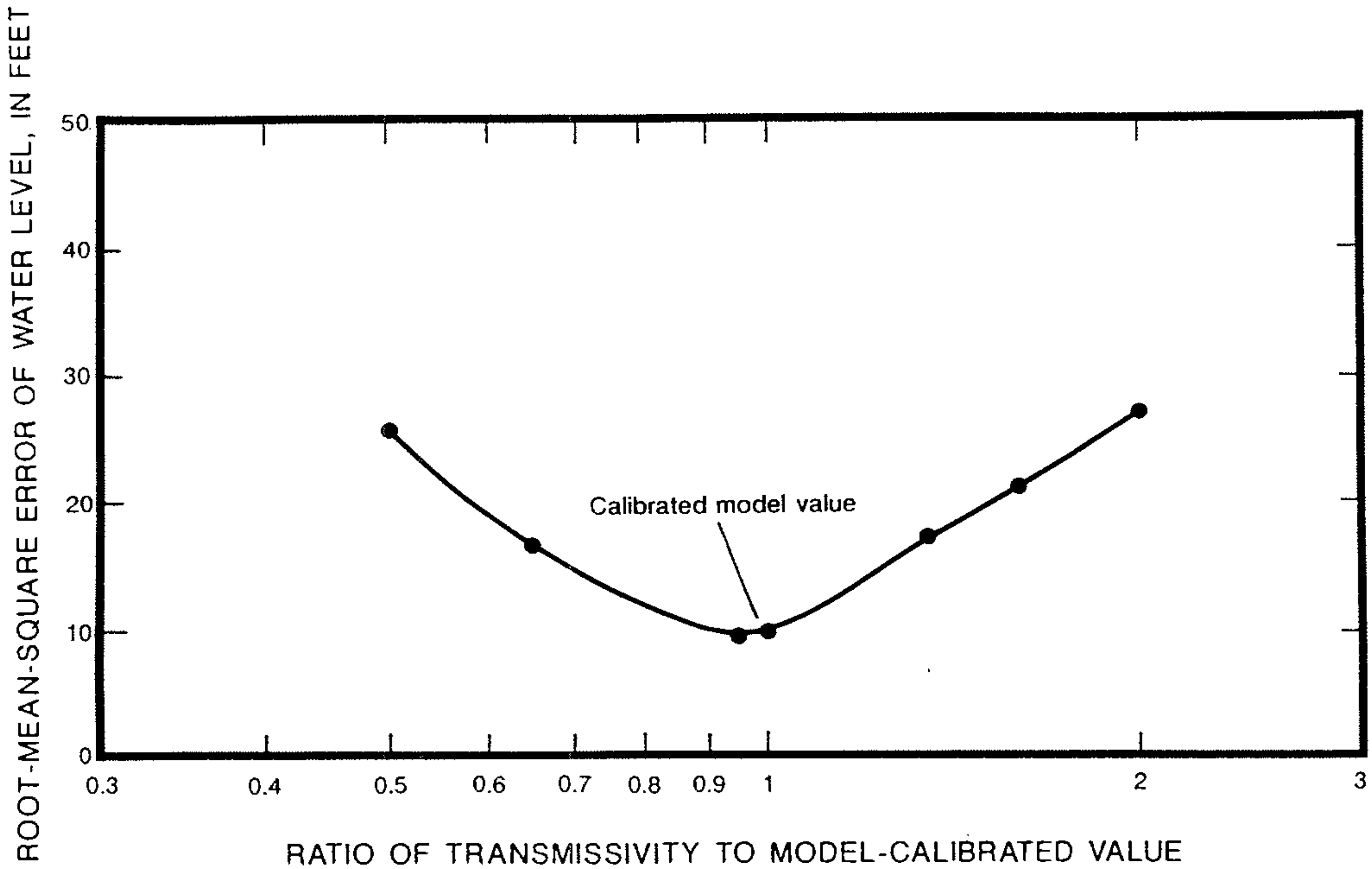


Figure 24.--Root-mean-square error of water level as a function of the ratio of adjusted transmissivity values to calibrated values.

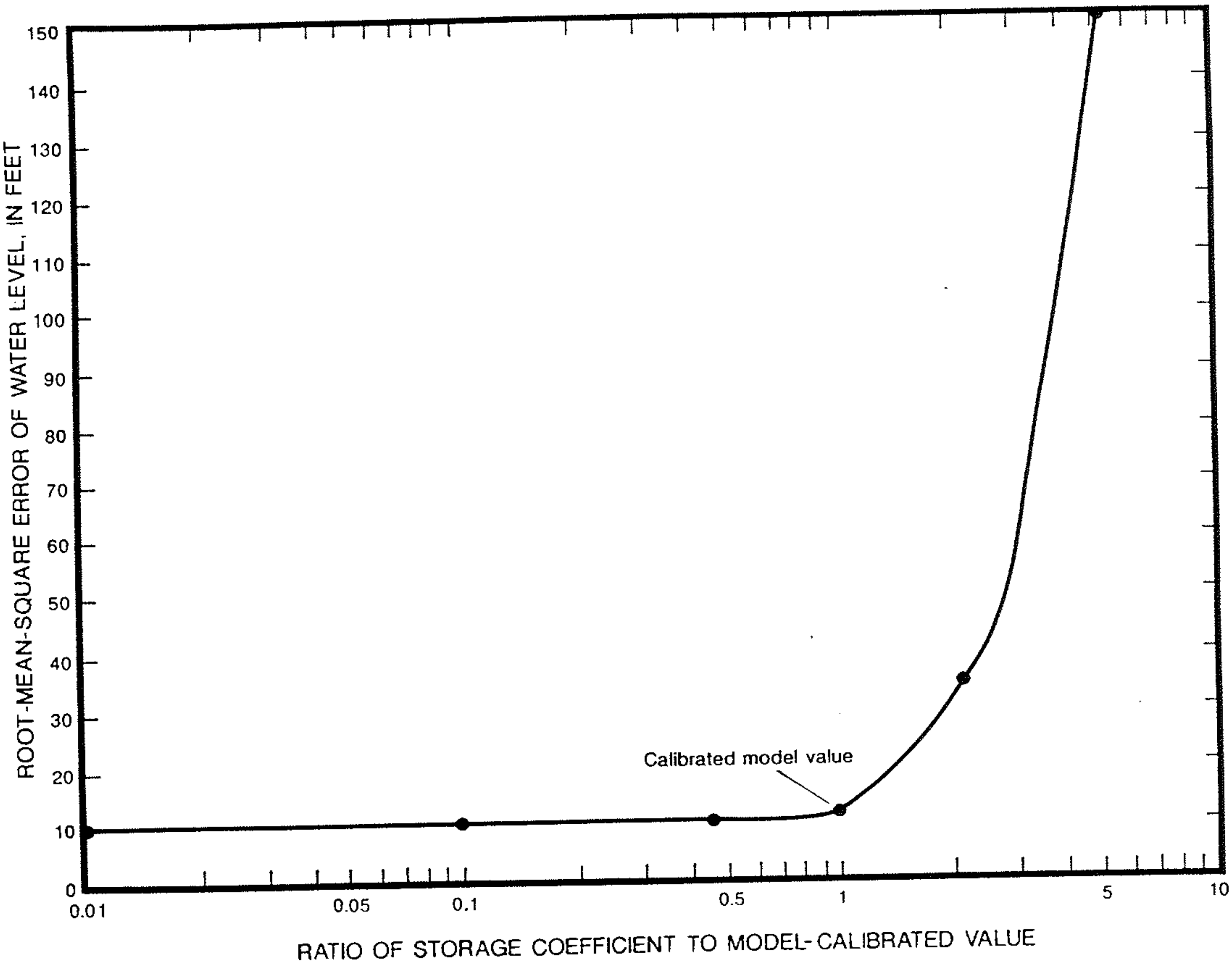


Figure 25.--Root-mean-square error of water level as a function of the ratio of adjusted storage-coefficient values to calibrated values.

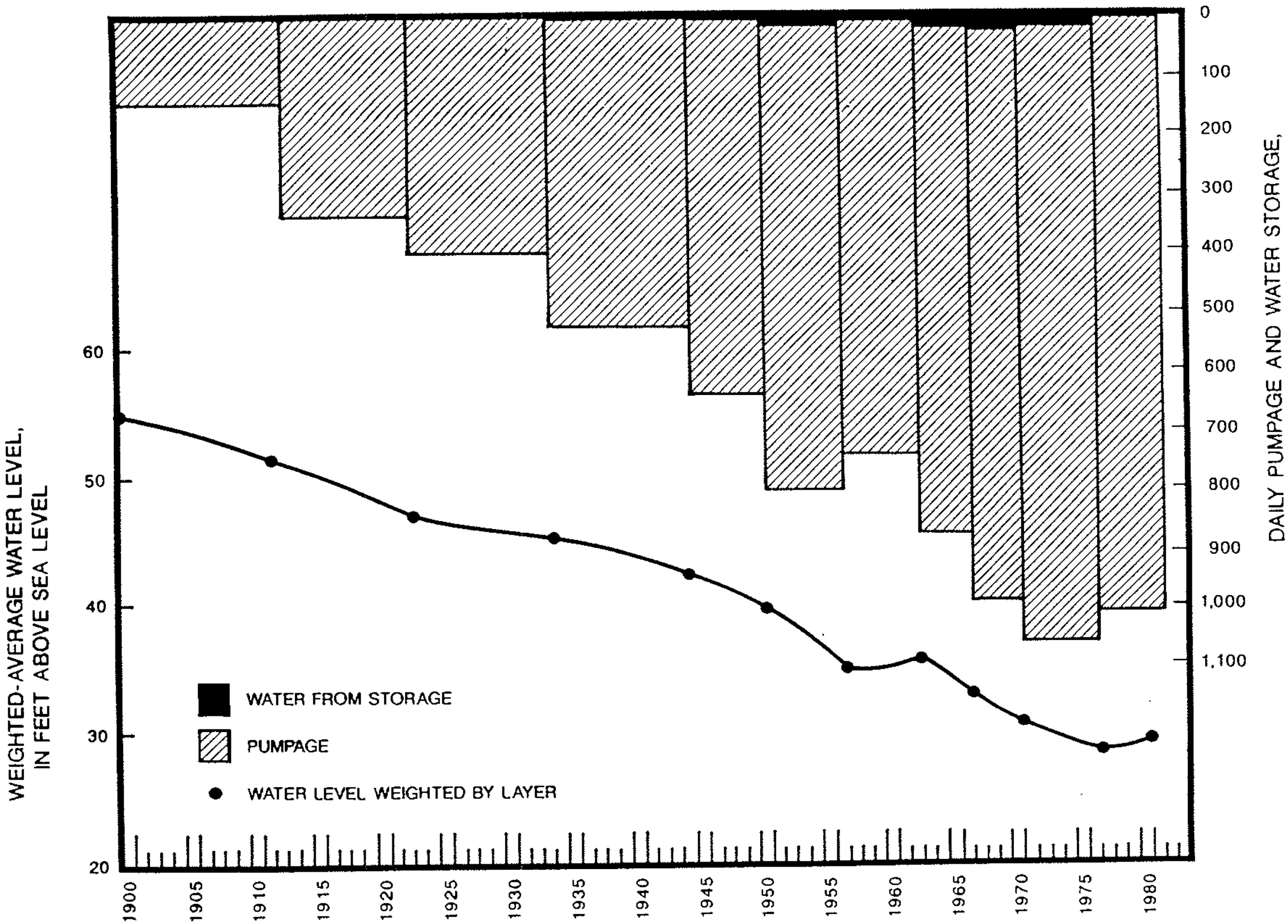


Figure 26.--Comparison of the fluctuations in weighted-average water level and pumpage as a function of time.

brated model and water levels from a simulation with a leakance one quarter of the calibrated value between layers 1 and 2 are shown in figure 27. Variations in transmissivity have their greatest effect in these same areas.

Because 90 percent of the water that enters the aquifer system under 1981 conditions leaves the system by pumpage at specified locations, variations in leakance, transmissivity, and storage did not significantly affect the total flow distribution simulated in the model. Ground-water gradients changed in inverse proportion to increases and decreases in leakance, transmissivity, and storage used in the sensitivity simulations.

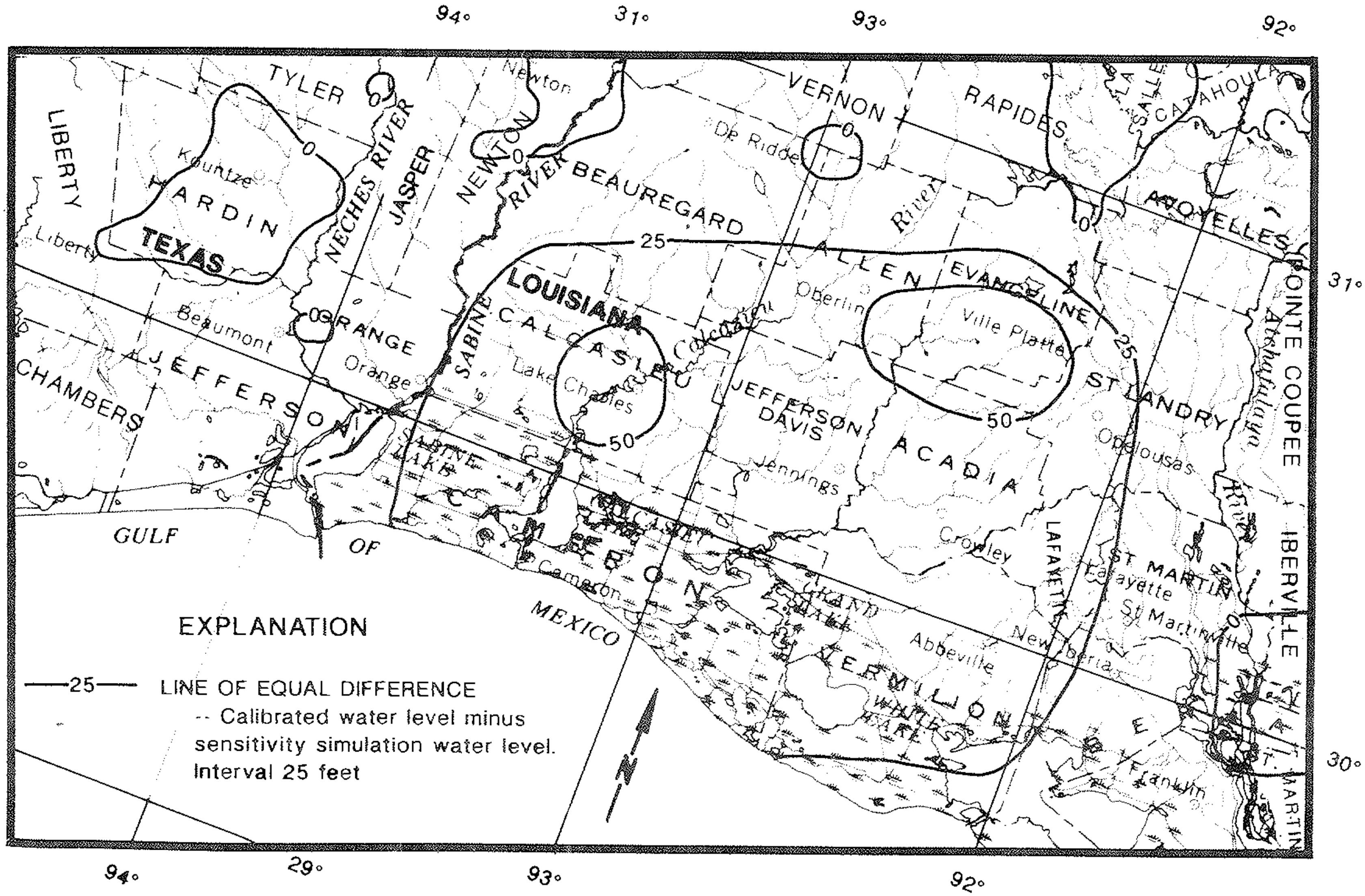
SIMULATED EFFECTS OF PUMPING

After the model was calibrated, a series of experiments were carried out to estimate the response of the aquifer system to changes in pumpage. The following conditions were simulated:

1. All pumpage was stopped after 1981, and the aquifer system was allowed to recover until the year 2064.
2. The pumpage was instantaneously increased by 50 percent at the beginning of 1982 and then held constant until the year 2064.
3. The pumpage was increased by 25 percent of the 1980 rate from 1982 to 2005 and by 50 percent of the 1980 rate from 2006 to 2040.
4. The pumpage was increased by 50 percent of the 1980 rate from 1982 to 2005 and by 100 percent of the 1980 rate from 2006 to 2040.
5. The pumpage was decreased by 25 percent of the 1980 rate from 1982 to 2005 and by 50 percent of the 1980 rate from 2006 to 2040.

The response of the system to the experiments is demonstrated by the weighted-average water level by layer in the aquifer system and water levels in specific blocks in highly stressed zones. Blocks (6,18) in layer 2 (upper Chicot aquifer in the rice-growing area) and (7,11) in layer 3 ("500-foot" sand in the Lake Charles industrial area) (fig. 12) are used to represent these highly stressed zones. The asymptotes in figures 28 through 31 represent the final steady-state water level after all transient effects have dissipated. In experiment 1, water levels recovered to approximately 80 percent of predevelopment levels 3 years after stopping all simulated pumpage (fig. 28). The system was within 3 percent of reaching steady-state conditions in approximately 15 to 25 years (1996-2006). In experiment 2, roughly 80 percent of the simulated decline in water levels occurred in the first 3 years of increased pumpage (fig. 29). Results of experiments 1 and 2 demonstrate the relatively rapid response of the aquifer system to changes in stress.

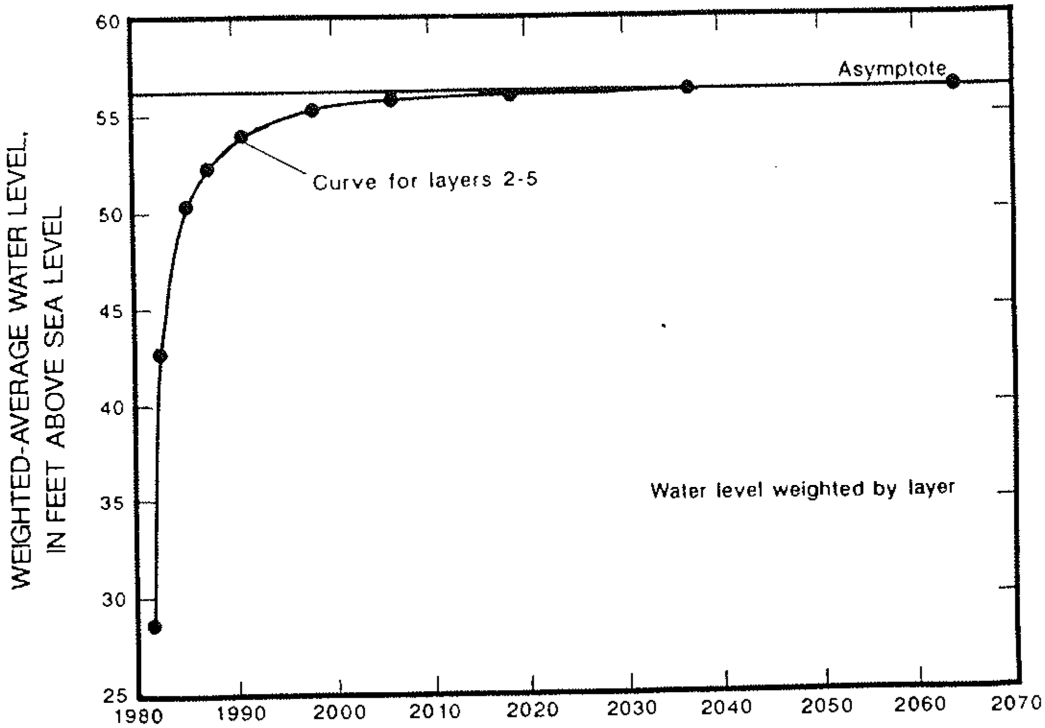
Experiments 3, 4, and 5 show transient response of the aquifer system to shorter periods of stress changes. The water-level response in block (7,11) in model layer 3 ("500-foot" sand) for each experiment (fig. 30) is typical of that of the aquifer system as a whole (fig. 31). In experiment 4, water levels would fall below the top of the upper Chicot aquifer and dewatering would begin in the Lake Charles and rice-growing areas 2 to 3 years after the second increase in pumping rates began in the year 2006. Although this model



Base from U.S. Geological Survey
State base map, 1:500,000

0 10 20 30 MILES
0 10 20 30 KILOMETERS

Figure 27.--Differences in water levels in model layer 2 (upper Chicot aquifer) due to a 75-percent decrease in the vertical hydraulic conductivity from calibrated values between layers 1 and 2.



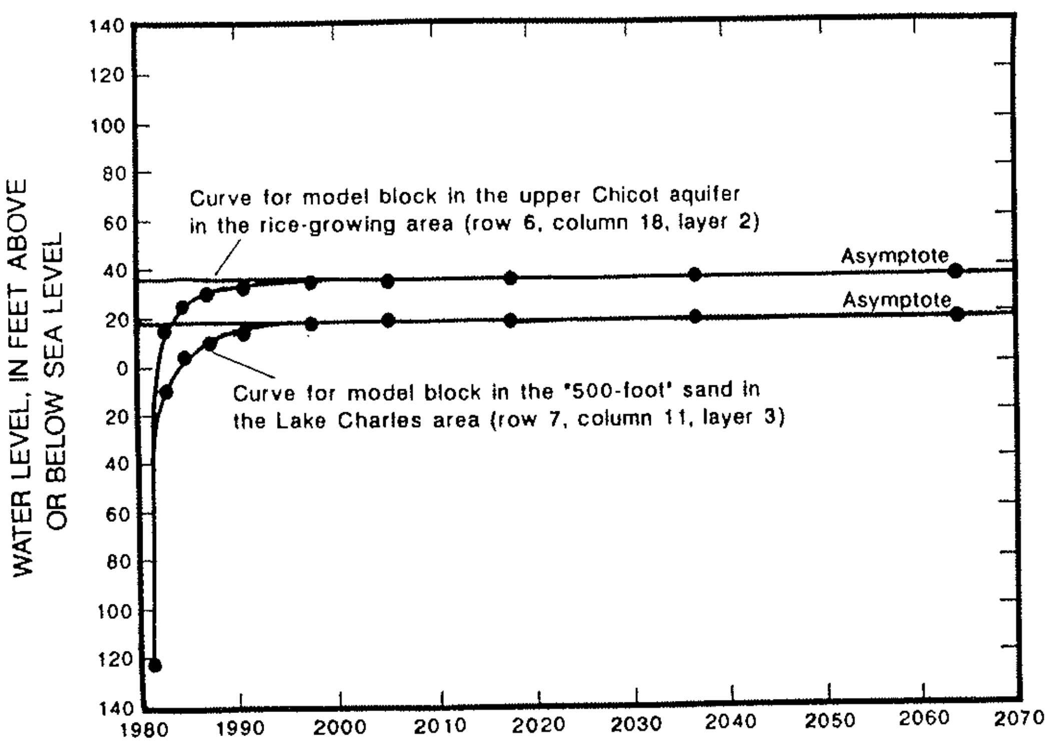


Figure 28.--Computed water levels resulting from experiment 1, stopping all simulated pumpage after 1981.

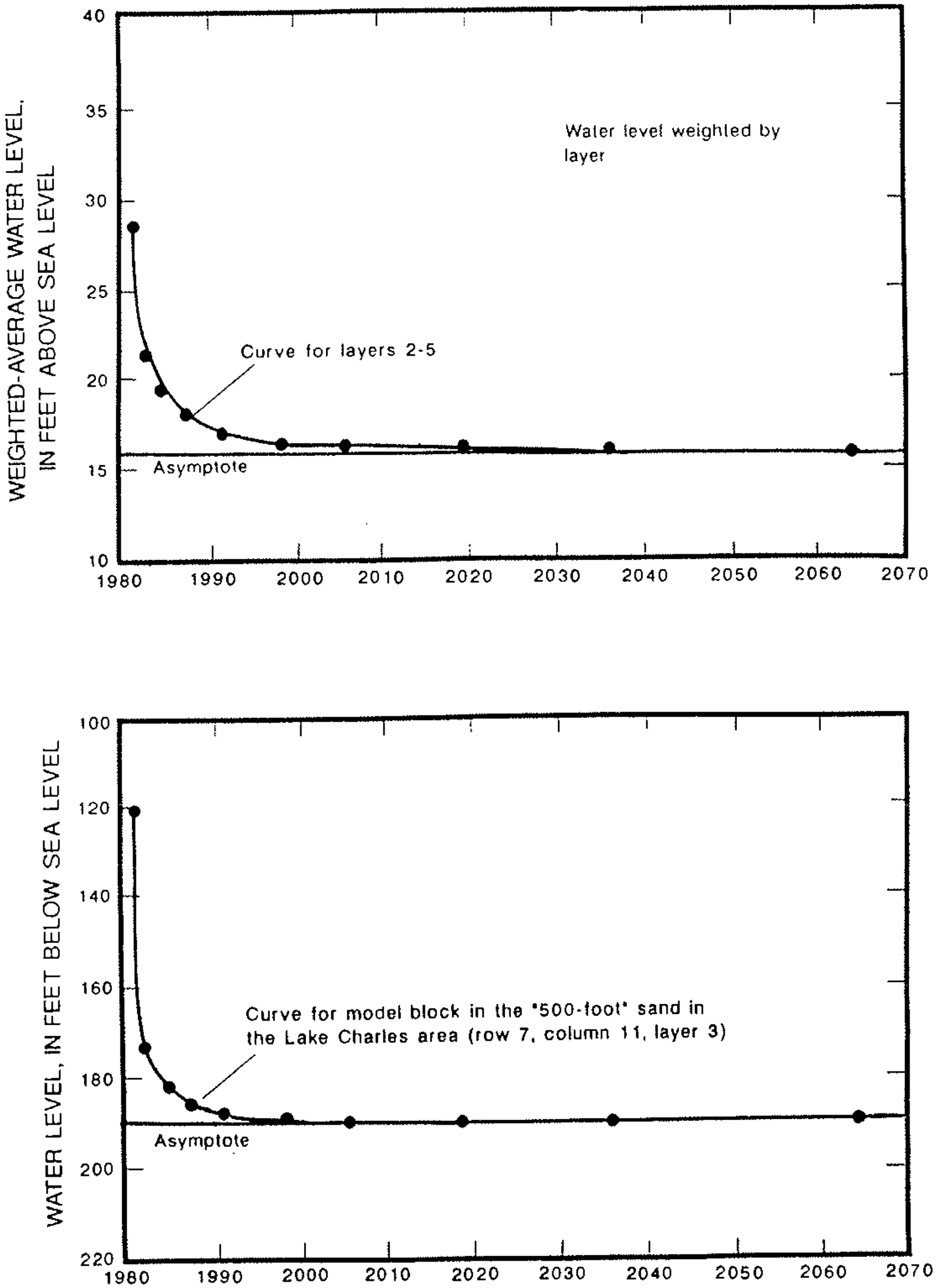


Figure 29.--Computed water levels resulting from experiment 2, simulating a pumping rate 50 percent larger than the 1980 pumping rate.

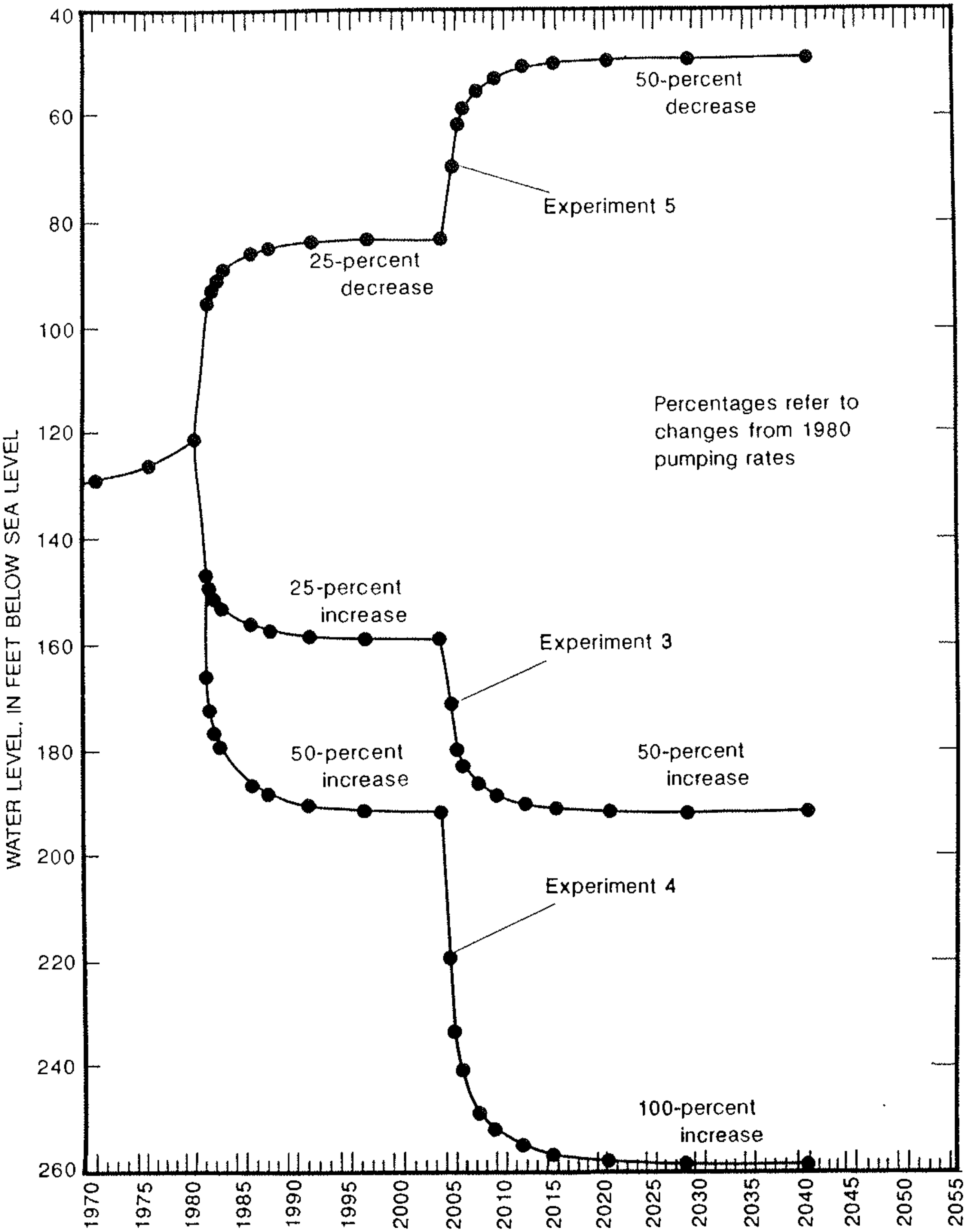


Figure 30.--Computed water levels in block (7,11) in the Lake Charles area in layer 3 resulting from changing pumping rates in experiments 3, 4, and 5.

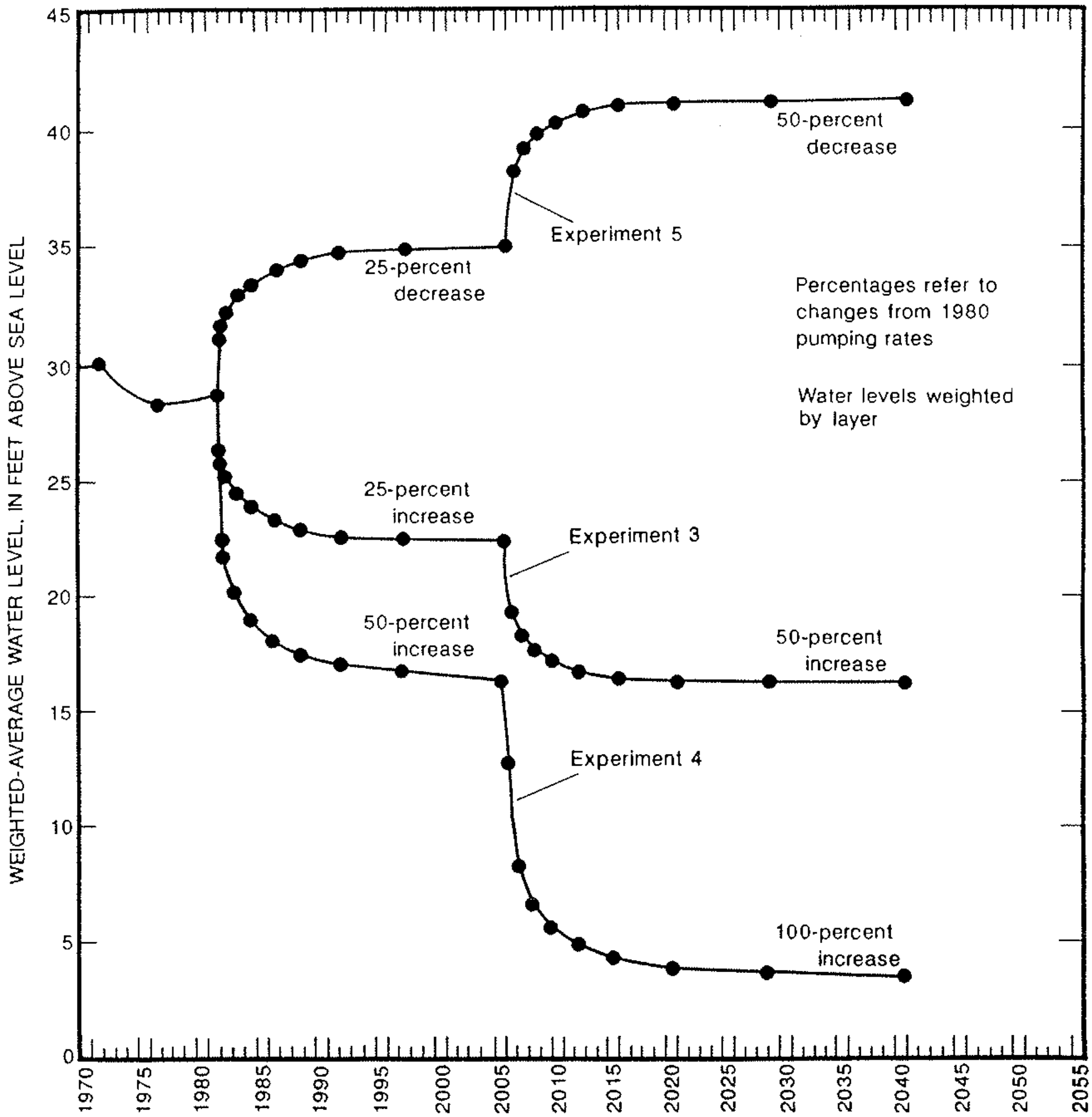


Figure 31.--Computed weighted-average water levels for layers 2 through 5 resulting from changing pumping rates in experiments 3, 4, and 5.

cannot be used to accurately determine the lateral and vertical extent of dewatering, indications are that only the Lake Charles industrial area would be significantly affected. Declines in water level are directly proportional to increases in pumpage for the areas tested in the aquifer system. The linear response of the system to pumpage can be used to interpolate drawdown for values of pumpage between those simulated in the two pumping experiments. This only applies to system-wide pumpage increases or decreases, not rate changes in individual wells.

Areally, the effects of uniformly increased pumpage are most pronounced from Lake Charles through the rice-growing area. Comparison of steady-state drawdowns from 1981 water levels for 50 percent (fig. 32) and 100 percent (fig. 33) increases in total pumpage indicates that the model-simulated drawdowns resulting from a 50-percent increase in pumpage are about half the drawdown resulting from a 100-percent increase. This comparison further illustrates the direct relation between pumpage and drawdown in the aquifer system.

Experiment 5 shows water-level recovery occurs rapidly for layers 2 through 5 as well as for individual blocks in response to decreases in pumpage (figs. 30 and 31). About 80 percent of the simulated recovery in water levels occurred in the first 3 years of decreased pumpage.

Water budgets are shown in table 5 for conditions ranging from predevelopment through pumpage at the highest rate simulated for the Chicot aquifer system. Most of the increases in flow in the aquifer system under developed conditions are attributable to vertical leakage in and near the pumping centers. Prior to development, more than 75 percent of the water entered the system in the outcrop area. Under 1981 conditions, recharge into the outcrop was 59 percent greater than the predevelopment recharge but only represented 28 percent of the water entering the Chicot aquifer system. Vertical leakage increased from 19 percent of flow in the aquifer system for predevelopment conditions to 67 percent for 1981 conditions. This trend would continue if pumping increases, as shown by the results with 50-percent and 100-percent increases in pumping rates.

In all model experiments, pumping rates can be maintained indefinitely with the available recharge. This is without consideration of the possibility of saltwater encroachment in the aquifers along the coast. Although the effects of saltwater encroachment were not addressed in this study, these effects need to be considered in the coastal areas of southwestern Louisiana (Nyman, 1984). These simulations show that dewatering of the upper Chicot aquifer will occur in the Lake Charles and rice-growing areas when stresses of twice the 1980 magnitude are applied. Localized drawdowns in individual wells or well fields will be more severe than the average values predicted for blocks. Seasonal and annual variations in pumping for rice irrigation will produce lower water levels periodically than the averages computed by the model.

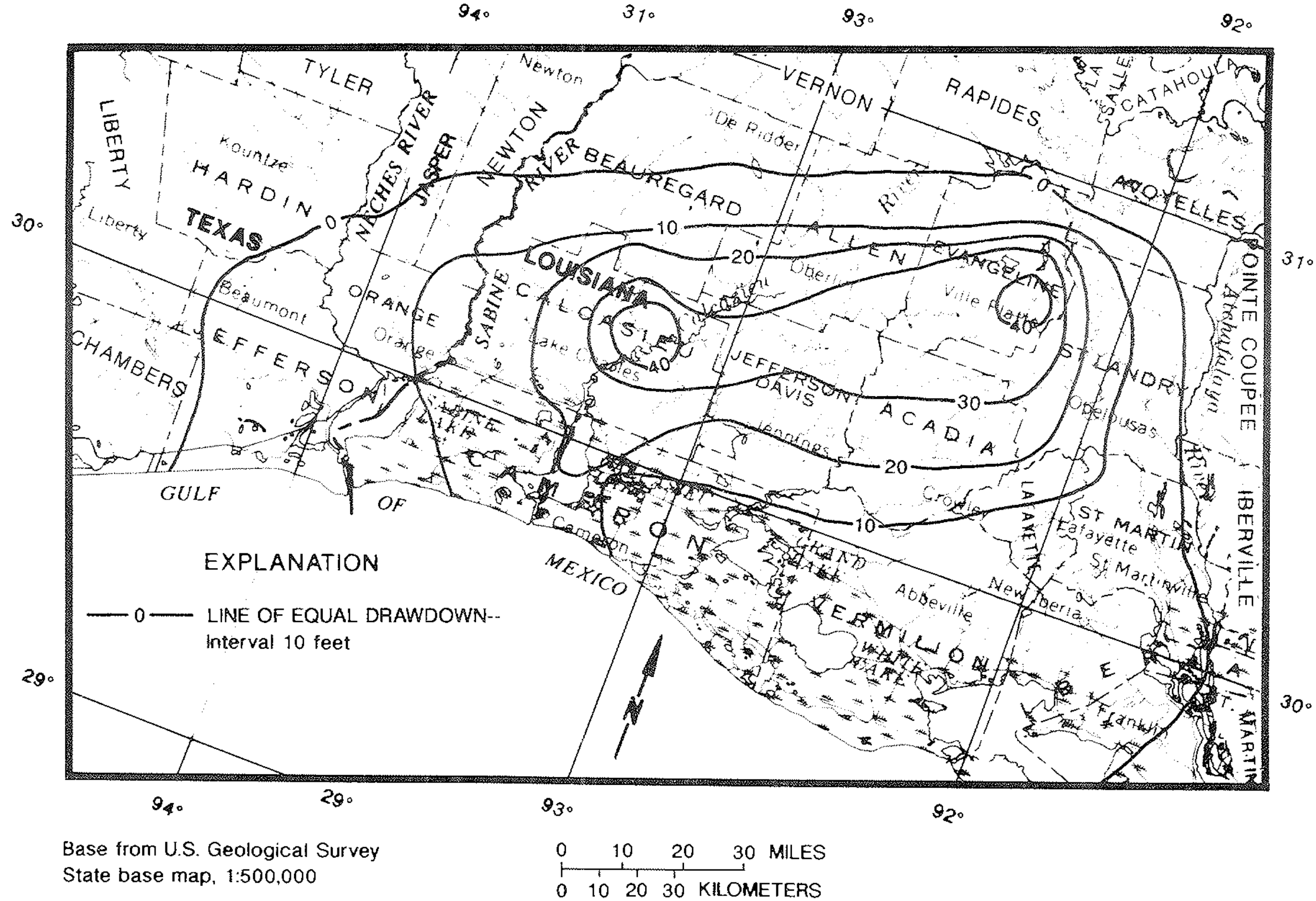
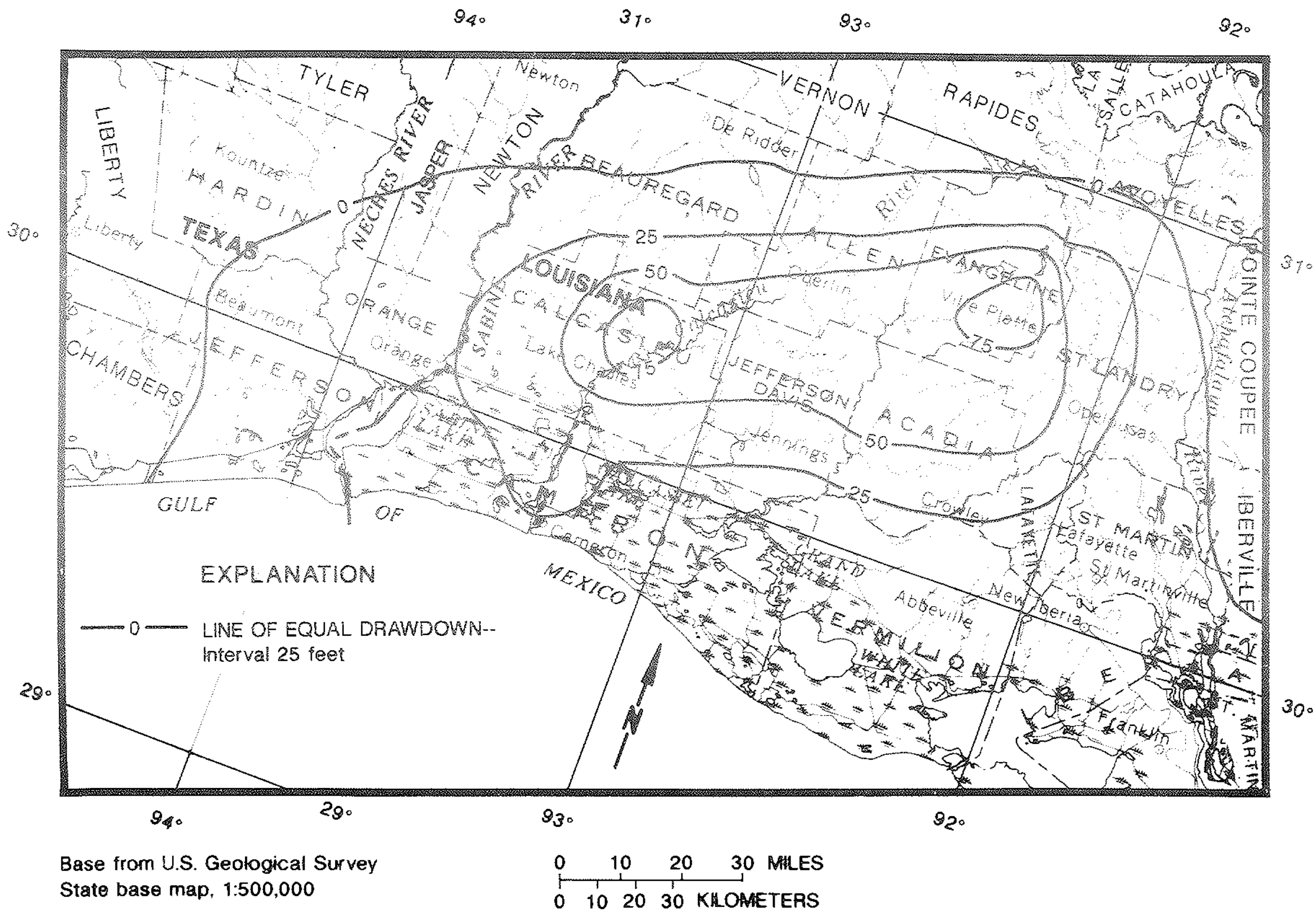


Figure 32.--Computed steady-state drawdowns from 1981 water levels in model layer 2 (upper Chicot aquifer) due to a simulated pumping rate 50 percent larger than the 1980 pumping rate.



Base from U.S. Geological Survey
State base map, 1:500,000

Figure 33.--Computed steady-state drawdowns from 1981 water levels in model layer 2 (upper Chicot aquifer) due to a simulated pumping rate 100 percent larger than the 1980 pumping rate.

Table 5.--Changes in the water budget of the Chicot aquifer system for increasing pumping rates through time

[Units are in million gallons per day]

Water source	Simulation period							
	Predevelopment		1981		2005 (50 percent greater pumpage than 1981)		2040 (100 percent greater pumpage than 1981)	
	Quantity of water	Percent of total inflow	Quantity of water	Percent of total inflow	Quantity of water	Percent of total inflow	Quantity of water	Percent of total inflow
Outcrop..........	199	76	316	28	355	23	403	20
Vertical leakage.........	48	19	738	67	1,113	72	1,500	74
Atchafalaya River basin.....	10	4	20	2	15	1	28	1
General-head boundary in the upper Chicot aquifer (model layer 2)........	3	1	25	2	64	4	89	5
Storage..........	0	0	9	1	5	0	3	0
Sum of all sources.........	260	100	1,108	100	1,552	100	2,023	100
Pumpage..........	0		995		1,493		1,991	

SUMMARY

Aquifers of the Chicot aquifer system supplied about 1 Bgal/d of water in 1980 and are the most heavily pumped aquifers in Louisiana. Ninety-five percent of the water pumped from the Chicot aquifer system was used for rice irrigation and industry. Records indicate that water levels in wells declined, on average, 1 ft/yr from 1900 to 1981 in the Lake Charles and rice-growing areas. Water levels have risen, on average, 2 ft/yr during the period 1982-85 because pumping rates during the period decreased by 38 percent to 616 Mgal/d.

The Chicot aquifer system is a complex series of alternating beds of unconsolidated sand, gravel, silt, and clay. Generally, the sands are very coarse, permeable, and thick. The Chicot aquifer system crops out in Louisiana in southern Vernon and Rapides Parishes and in northern Beauregard, Allen, and Evangeline Parishes. Confining clay beds within the aquifer system generally are thin and discontinuous in the outcrop area. Surface clay ranges from as little as 1 ft in thickness along the southern edge of the outcrop area where water in the aquifer system becomes confined to as much as 200 ft downdip.

Prior to ground-water development, water flowed from recharge areas where the aquifers outcrop in southern Vernon and Rapides Parishes and in northern Beauregard, Allen, and Evangeline Parishes southward to discharge areas along the coast and eastward to the Atchafalaya River basin. Discharge took place upward through confining clay beds in the coastal-wetland areas and in the Atchafalaya River basin. Development has lowered water levels south of the outcrop and reversed the direction of flow in the aquifers south of Lake Charles and south and east of the rice-growing area.

A five-layer, finite-difference, digital ground-water flow model was developed to simulate flow in the Chicot aquifer system and to investigate the effects of present and future pumpage. Model calibration was completed in two phases. The first phase involved matching 1980 conditions treated as steady state. The second phase involved transient calibration to match conditions in the aquifer system from the start of development to 1981. Model-computed water levels generally compared closely with observed levels.

Results from the calibrated model show that development from the early 1900's to 1981 has significantly altered flow patterns and rates in the Chicot aquifer system. Approximately a fourfold increase (from 259 to 1,113 Mgal/d) in flow through the aquifer system has occurred. Vertical leakage is the largest component of recharge to the Chicot aquifer system under 1981 conditions. In 1981, 67 percent of the total flow in the aquifer system came from vertical leakage. Only 1 percent (about 9 Mgal/d) of the flow in the aquifer system came from storage.

The sensitivity of the model to simulated changes in vertical hydraulic conductivity, transmissivity, and storage varied. The effects of storage are relatively insignificant in the Chicot aquifer system, where transient effects are of short duration. For values of transmissivity and vertical leakance near the calibrated values, the model is most sensitive to changes in the values of transmissivity. Near the lower end of the range of uncertainty of these hydraulic characteristics, the model is most sensitive to changes in vertical leakance.

Analysis of simulations indicates that transient effects last for a relatively brief time in the aquifer system. High pumpages can be maintained indefinitely with the recharge available to the Chicot aquifer system. Salt-water encroachment along the coast is possible, but its effects were not addressed in this study. The upper Chicot aquifer would be dewatered in the Lake Charles and rice-growing areas if sustained withdrawal rates increase to more than 150 percent of the 1980 withdrawal rate. Model results indicate that only the Lake Charles industrial area would be significantly affected.

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